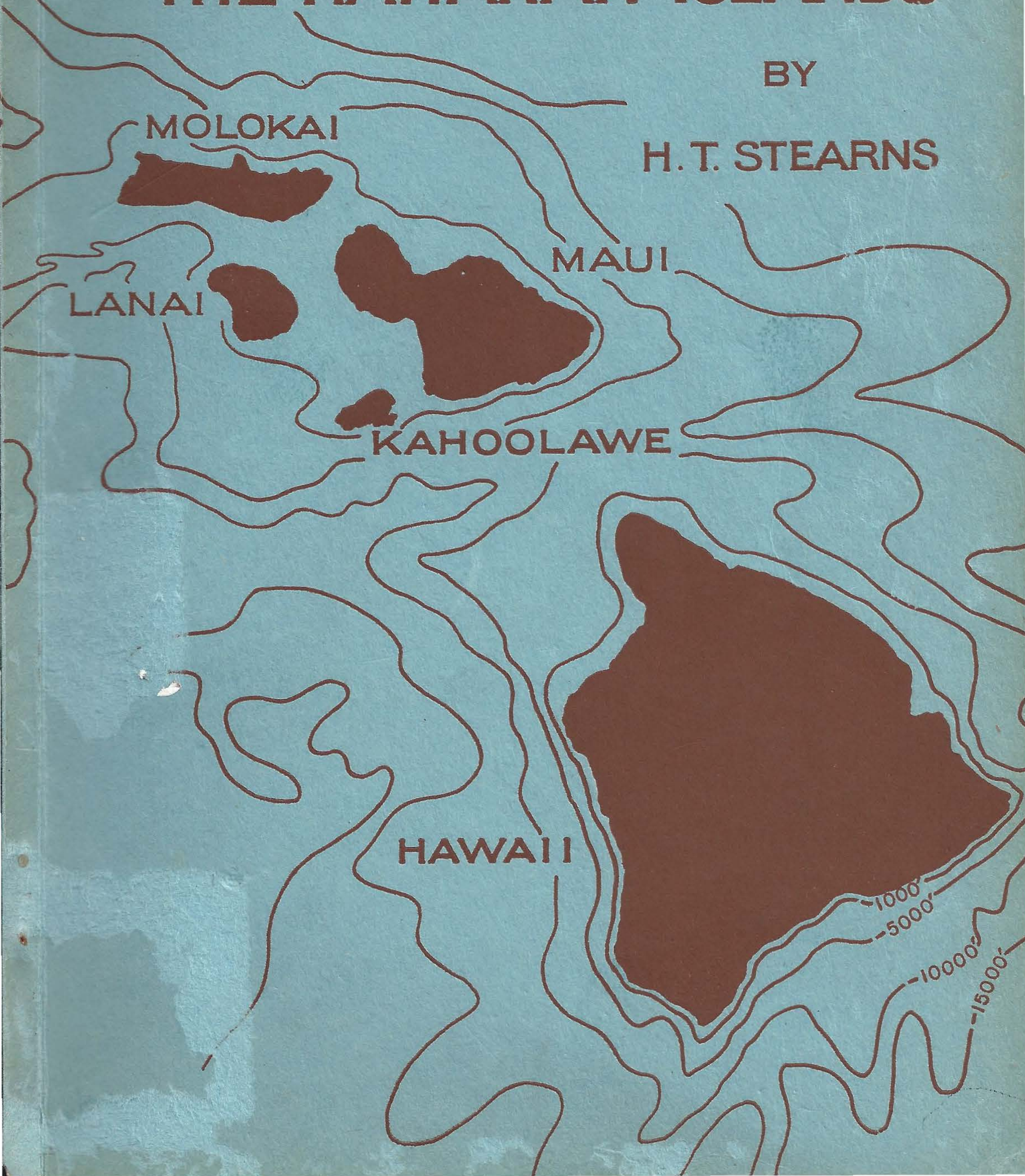
GEOLOGY OF THE HAWAIIAN ISLANDS

BY

H. T. STEARNS



Frontispiece.—Hanalei Valley, Kauai. The low plateau is composed of lavas of the Koloa volcanic series and the high mountains are composed of rocks of the Waimea volcanic series. Photo by Mike Roberts.

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BY

HAROLD T. STEARNS

District Geologist, U. S. Geological Survey

BULLETIN 8

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CONTENTS

PAGE

Abstract 1
Introduction 1
Geography and climate 2
Geomorphology 5
Geology 16
  General statement 16
  Island of Hawaii 25
    Mauna Kea 30
    Mauna Loa 32
    Hualalai 37
    Kohala 38
    Kilauea 43
  Island of Maui 49
    West Maui 49
    East Maui or Haleakala 59
  Island of Kahoolawe 63
  Island of Lanai 67
  Island of Molokai 69
    West Molokai 69
    East Molokai 71
    Kalaupapa 73
  Island of Oahu 73
    Waianae Range 77
    Koolau Range 78
  Island of Kauai 82
  Island of Niihau 90
  Offshore islets 93
  Leeward Islands 93
Geologic history 95
Selected bibliography of the geology of the Hawaiian Islands .. 100
Index 102

PAGE

Supplement 106

Geomorphology 106

Geology 106

Island of Hawaii 106

Island of Kauai 107

Ages of the Hawaiian Rocks 110

ILLUSTRATIONS

PLATES PAGE

View of Hanalei Valley, Kauai .... *frontispiece*

1. Map of the larger islands of Hawaii, their known rift zones, submarine contours in feet, and principal islets .... *facing page* 2
2. Halawa Valley, Molokai, a typical amphitheater-headed valley 6
3. Stages 1 and 2 in geologic development of Oahu 9
4. Stages 3 and 4 in geologic development of Oahu 10
5. Stages 5 and 6 in geologic development of Oahu 11
6. Stages 7 and 8 in geologic development of Oahu 12
7. "Curtain-of-fire" formed by coalescing lava fountains, Mauna Loa Volcano, Hawaii 15
8. Summit of Mauna Loa Volcano, Hawaii showing Mokuaweoweo and pit craters 18
9. Halemaumau, Hawaii in eruption September 1934 24
10. Summits of Mauna Kea and Mauna Loa volcanoes, Hawaii 31
11. Eruptions of Mauna Loa Volcano, Hawaii 35
12. Waipio Valley, Hawaii 42
13. Summit depression of Haleakala, Maui 50
14. The Needle, Iao Valley, West Maui 51
15. Stages 1 and 2 in the geologic development of Maui 55
16. Stages 3 and 4 in the geologic development of Maui 56
17. Stages 5 and 6 in the geologic development of Maui 57
18. Stages 7 and 8 in the geologic development of Maui 58
19. Honokahau Canyon, West Maui 60
20. West Maui Mountains behind Lahaina 62
21. Aerial mosaic of Kahoolawe Island 64
22. Lanai as seen from West Maui 66
23. The great cliff on the north side of East Molokai 70
24. The Pali on Oahu 76
25. Makua Cave, Oahu Island 79
26. Kaau Crater, Oahu Island 80
27. Napali Coast, Kauai Island 84
28. Waimea Canyon, Kauai Island 86
29. Haupu Ridge, Kauai Island 88

FIGURES PAGE

1. Map and profile of the Hawaiian Archipelago showing submarine contours 4
2. Diagram illustrating the formation of amphitheater-headed valleys .. 7
3. Three stages showing the geologic history of a sea cliff veneered with lava 13
4. Profiles of cognate secondary cones 17
5. Eight stages in the geologic history of a volcanic island in the central Pacific 20
6. Sections of typical bulbous domes 21
7. Map of Hawaii showing historic lava flows 25
8. Graph showing periods of activity of Kilauea and Mauna Loa volcanoes 26
9. Geologic map of the island of Hawaii 29

FIGURES PAGE

10. Graph showing the location and altitude of eruptions of Mauna Loa Volcano, 1832–1942 32
11. Diagrams showing the origin of Puu Waawaa, Hawaii 37
12. Four stages in the development of Waipio and Waimanu Valleys, Hawaii 40
13. Hypothetical relation of Kilauea and Mauna Loa volcanoes with the interior of the earth 44
14. Diagram illustrating the relation of faulting to successive lava flows 48
15. Geologic map of the island of Maui 52
16. Geologic map and sections of the island of Kahoolawe 65
17. Geologic map of the island of Lanai 68
18. Geologic map of the island of Molokai 72
19. Geologic map of the island of Oahu 74
20. Map of Oahu showing emerged and fringing reefs 81
21. Map of southeastern Oahu showing secondary post-Koolau volcanic vents 82
22. Reconnaissance geologic map of the island of Kauai 83
23. Sections showing the development of the Napali Cliff, Kauai 90
24. Geologic map of the island of Niihau 92
25. The Hawaiian archipelago near the end of the Pliocene 97
26. The Hawaiian archipelago during the minus 300-foot stand of the sea in the early (?) Pleistocene 98
27. The Hawaiian archipelago at the present time 99

GEOLOGY OF THE HAWAIIAN ISLANDS

By Harold T. Stearns

ABSTRACT

A brief summary of the geography, climate, and geomorphology is given. Streams develop slowly after the extinction of a volcano because of the high permeability of the rocks. Once established they cut rapidly because of the steep slopes and fractured condition of the rocks. Stream erosion varies enormously on different slopes of the same mountain due to the great differences in rainfall and to other causes. Six reasons are given for the development of amphitheater-headed valleys. Marine erosion has formed cliffs as much as 1,000 feet high on the leeward side and 3,000 feet high on the windward side of some of the domes. The islands have undergone a complex series of emergences and submergences leaving marine fossiliferous limestone up to 1,070 feet above sea level and valleys drowned more than 1,200 feet. Twelve terrace levels are recognized. Some are definitely eustatic.

A synopsis is given of the present knowledge of the geology of each volcanic mountain, as well as a table of the rock units, and geologic maps of all major islands. The volcanoes pass through four major phases between birth and extinction and are built around one minor and two major rift zones. The volcanoes began their history above sea level in the Tertiary. Most of them became dormant either before or during the early Quaternary. Activity was renewed in the late Quaternary. Mauna Kea was glaciated in the late Pleistocene. The character of each islet in the archipelago is tabulated.

INTRODUCTION

This paper is a synopsis of the geology of the Hawaiian Islands. The writer has spent 15 years mapping the geology and ground-water resources of the islands for the Geological Survey in financial cooperation with the Territory of Hawaii. The interior of Kauai has not yet been fully investigated. The islets between Kauai and Midway have been seen only from a plane. This paper was written in 1939 but its publication was delayed by the war. It has been slightly revised since.

The writer acknowledges the valuable criticisms of Messrs. T. A. Jaggar, O. E. Meinzer, G. A. Macdonald, C. S. Ross, and M. H. Carson. James Y. Nitta and Ben Norris prepared the illustrations.

GEOGRAPHY AND CLIMATE

The Hawaiian Archipelago is a group of islands, reefs, and shoals, strung out from southeast to northwest for 1,600 miles between 154° 40′ and 178° 75′ W. longitude and 18° 54′ to 28° 15′ N. latitude (fig. 1 and lower inset map, pl. 1). Exclusive of Midway, which is an important airplane base and which for many years has been the site of a cable station, the inhabited islands lie at the southeast end of the archipelago. Hawaii is the largest and southeasternmost island, and has the only active volcanoes. Honolulu, the principal city and capital, is on Oahu, 2,091 miles southwest of San Francisco, and is a port of call for ships en route from the west coast of North America to the Antipodes and to the Orient.

A detailed map showing submarine contours of the larger islands is given in plate 1. The volcanic peaks which form the islands are shown graphically in relation to each other in the upper inset, plate 1. Important data regarding the major islands are given in the accompanying table.

Area, altitude, maximum dimensions, population, and principal city of each of the larger islands

Island	Area (sq. mi.)	Altitude (feet)	Maximum distance (miles)		Population[a]	Principal city
			North-south	East-west		
Hawaii	4,030	13.784	87.3	75.3	73,276	Hilo
Maui	728	10,025	25.0	38.4	46,919	Wailuku
Oahu	604	4,025	40.0	26.0	257,664	Honolulu
Kauai	555	5,170	24.5	29.9	35,636	Lihue
Molokai	260	4,970	10.1	37.0	5,840	Kaunakakai
Lanai	141	3,370	13.3	13.0	3,720	Lanai City
Niihau	72	1,281	9.7	9.0	182	None
Kahoolawe ...	45	1,477	6.4	10.9	1	None
Total	6,435	....	....	....	422,738	....

[a] According to U. S. Census, 1940.

Explanation of Plate 1.

The Contours below —10,000 feet lack control in many places. Lower inset map shows position of the Hawaiian Archipelago in the Pacific Ocean, and upper inset shows profiles of the volcanic peaks of the main islands. The islets are 1. Kaula; 2. Kuakamoku; 3. Lehua; 4. Kalanipuao; 5. Mokuaeae; 6. Mokuauia; 7. Kukuihoolua; 8, Mokolii; 9. Kapapa; 10. Kekepa; 11. Moku o Loe; 12. Moku Manu; 13. Mokolea; 14. Papoia; 15. Mokulua; 16. Manana; 17. Kaohikaipu; 18. Mokuoeo; 19. Ford Island; 20. Mokapu; 21. Okala; 22. Mokohola; 23. Mokuhooniki; 24. Nanahoa; 25. Moku Naio; 26. Poopoo; 27. Puupehe; 28. Mokeehia; 29. Hulu; 30. Papanui o Kane; 31. Keopuka; 32. Alau; 33. Molokini; 34. Puu Koae; 35. Mokupuku; 36. Paoakalani; 37. Cocoanut Island; 38. Mokuokahailani; 39. Keaoi.

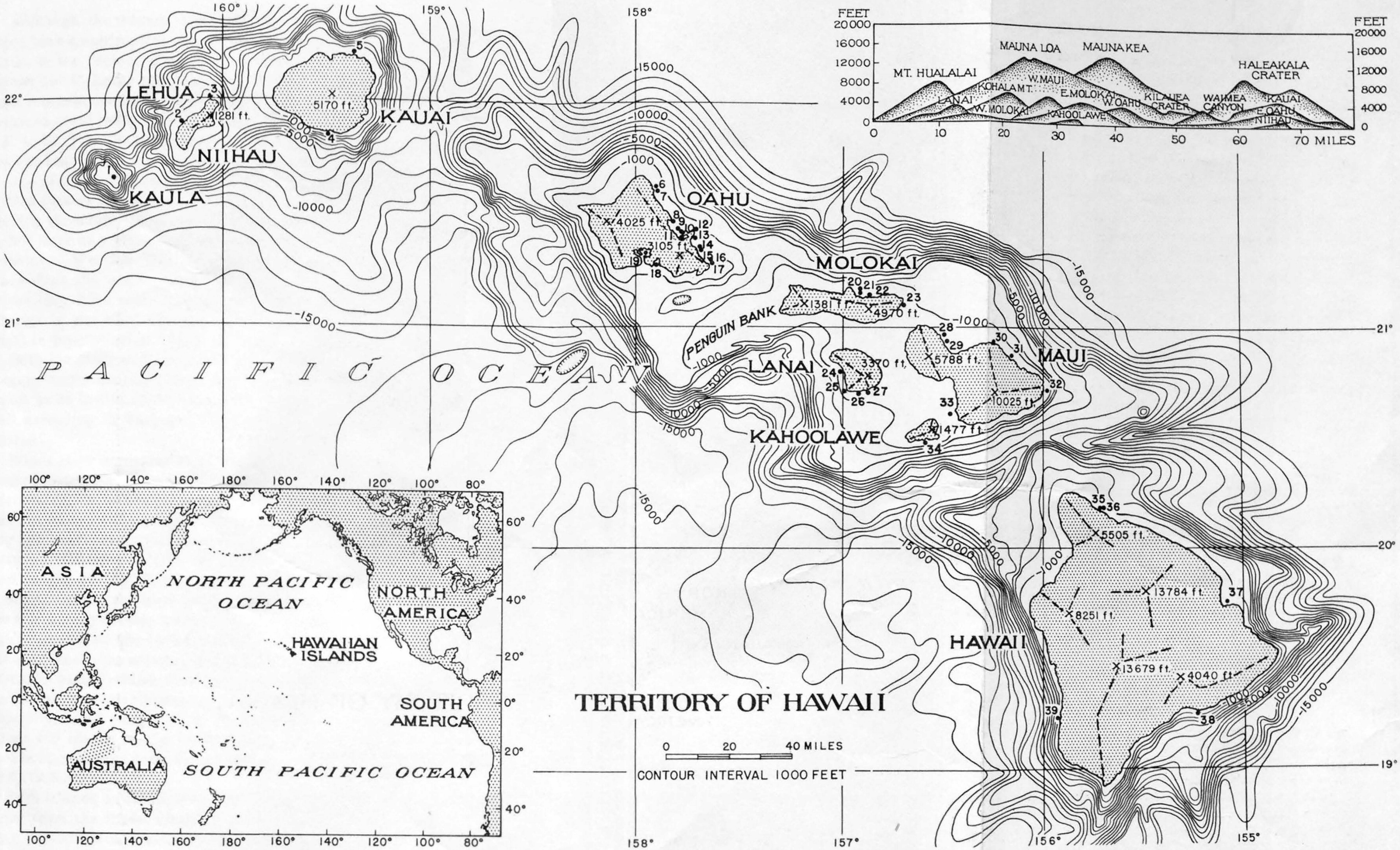


Plate 1. MAP OF THE LARGER ISLANDS OF HAWAII, THEIR KNOWN RIFT ZONES, SUBMARINE CONTOURS IN FEET, AND PRINCIPAL ISLETS. (Explanation of numbers on facing page.)

Although the islands are at the northern margin of the tropics, they have a subtropical climate because cool waters from Bering Sea drift to the region. The temperature of the surrounding waters is about 10° F. lower than that of other regions of the same latitude; and this relative coolness is, in part, the reason for the poor development of coral reefs. The ocean at Waikiki, Oahu, ranges from about 70° to 85° F.[1] The temperature of the air ranges from below freezing on the high peaks to about 97° F. at sea level on the leeward coasts.

The Hawaiian Islands lie in the belt of northeasterly trade winds which persist throughout the year, but are occasionally interrupted during the winter by southerly or "kona" winds which blow for only a few days at a time. The mean direction of the trade winds is not constant. Weather Bureau records for the decade following 1900 show that the winds veered progressively to the east, but in late years they have shifted slowly back toward the north again. This change in the wind direction is important because the consequent shift in precipitation affects the erosive power of streams.

Both the trade and southerly winds bring rain to the islands. The heavy storms usually come from the south. During such storms as much as 24 inches of rain has been recorded in four hours, and rainfall exceeding 20 inches in 24 hours has been recorded in several places.

Winds blow across miles of ocean before reaching the islands and consequently arrive laden with moisture. As they rise over the mountains, the winds are cooled and drop their moisture. The northeastern sides of the islands are usually wettest because the prevailing wind is from that direction. The maximum precipitation occurs between altitudes of 2,000 and 6,000 feet depending upon the form and height of the island. Above 6,000 feet the precipitation decreases, making the high peaks semiarid. As the winds descend the lee slopes, they become warmer, drying winds, causing arid and semiarid climates on the leeward sides of the islands. On the island of Hawaii, where the mountains are sufficiently high to pierce the layer of trade winds, eddies result in prevailing southwest winds on the lee side so that the climate in the leeward districts is fairly wet. The annual rainfall ranges from 10 inches or less on the lee coasts to about 450 inches in the wettest belts. In one year more than 600 inches of rain was recorded on the summit of Kauai at an altitude of 5,170 feet.

Such islands as Kahoolawe and Lanai are relatively low and sheltered from the trade winds by other islands and consequently are very dry. In windy seasons ribbon-shaped dust clouds from these two islands commonly extend many miles over the ocean.

[1] A temperature of 90° F. was recorded in August 1934, but this may have been an error because the readings are made by hotel attendants, and the second highest reading is 85° F.

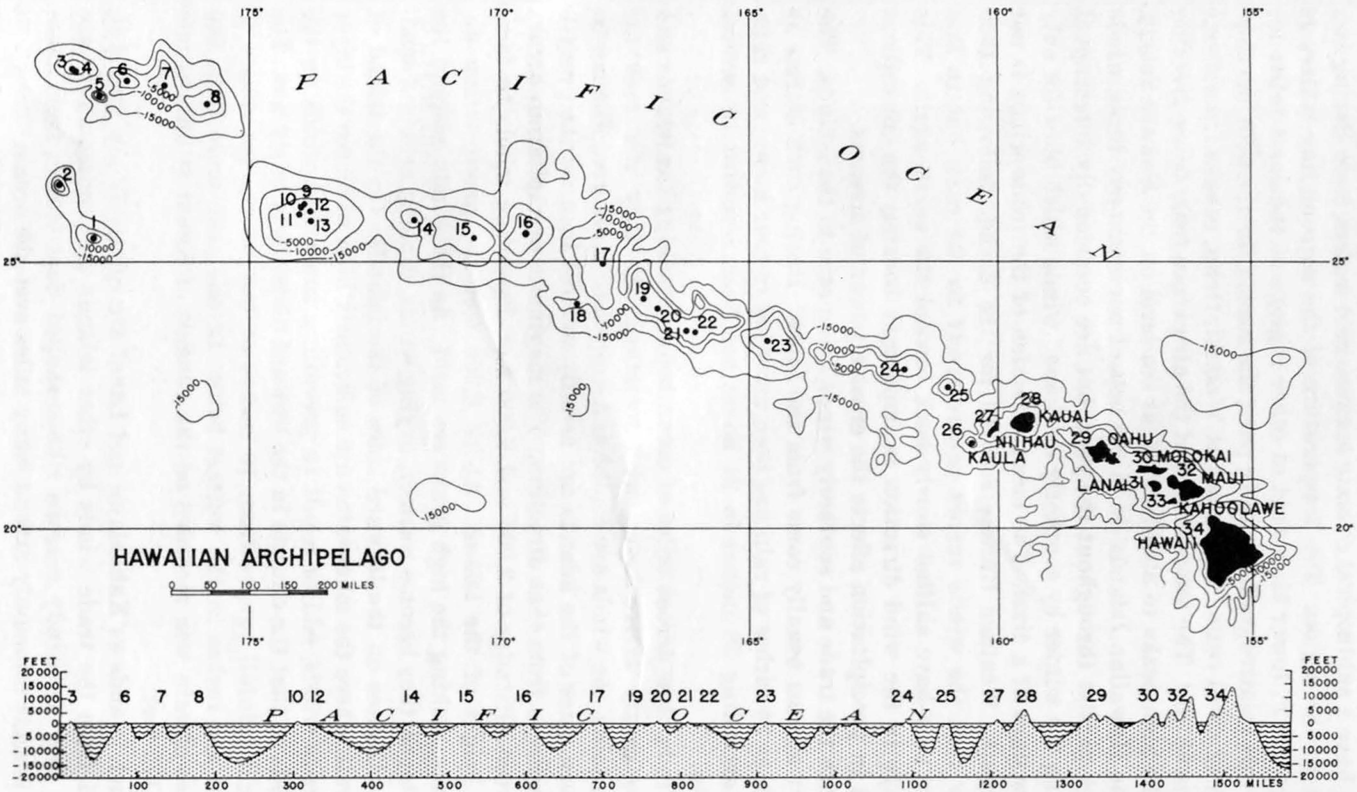


Figure 1. Map and profile of the Hawaiian Archipelago showing submarine contours in feet. Explanation of numbers on facing page.

GEOMORPHOLOGY

The major islands are basaltic volcanic domes in various stages of dissection. Oahu and Niihau have the only extensive coastal plains. The great permeability of the coral rock and basalt has an important bearing on the geomorphology of the islands. For some time after the cessation of volcanic activity, streams are unable to develop water courses because the surface is highly porous. For example, even though the rainfall is high, stream channels are not developed on most of Kilauea Volcano. Because temperatures are uniformly high and, except on high peaks, not below freezing, chemical weathering dominates over mechanical disintegration. Gradually thick lateritic soils form and reduce the porosity of the slopes, and stream courses are able to develop. Even though flashy, the streams are powerful agents of destruction because of the steep slopes and fractured condition of the rocks.

The amount of stream erosion varies enormously on the different slopes of the same dome. The northeastern slopes of the larger islands may be incised by deep canyons because of the high rainfall, whereas the leeward sides may have relatively small gulches. Anomalous physiographic relationships are common. On some of the domes, high fault scarps have protected one slope from lava flows while another slope was being covered. Differences in the age of the rocks on the two sides of a mountain give rise generally to vastly discordant stages of erosion; for example, on the Waianae Range, Oahu, the leeward slope is older, hence much more eroded than the windward side.[2] Further, the rate of erosion on a volcano may be slackened by the growth of another volcano to the windward, as happened when the Koolau dome cut off the trade winds from the Waianae dome (pls. 3–6).

[2] Stearns, H. T., Geologic map and guide of the island of Oahu, Hawaii: Hawaii Div. Hydrography, Bull. 2, 1939.

←

Explanation of figure 1.

1. Unnamed shoal; 2. Bensaleux Reef; 3. Kure or Ocean Island; 4. Green Island; 5. Nero Bank; 6. Midway Islands; 7. Gambia Shoal; 8. Pearl and Hermes Reef; 9. Lisianski Island; 10. Fisher Reef; 11. Minor Reef; 12. Neva Shoal; 13. Springbank Reef; 14. Laysan Island; 15. Maro (Dowsett) Reef; 16. Raita Bank; 17. Gardner Pinnacles; 18. Two Brothers Reef; 19. St. Rogatien Bank; 20. Brooks Banks; 21. La Pérouse Pinnacle; 22. French Frigate Shoal; 23. Necker Island; 24. Nihoa; 25. Unnamed shoal; 26. Kaula; 27. Niihau; 28. Kauai; 29. Oahu; 30. Molokai; 31. Lanai; 32. Maui; 33. Kahoolawe; 34. Hawaii.

Plate 2. Halawa Valley, Molokai, a typical amphitheater-headed valley. Photo by U.S.A.A.F.

The unusually high rainfall zoned by altitude, together with the steep radial drainage developed on alternating layers of weak and strong vertically jointed rocks dipping seaward, have produced on these islands a distinctive type of valley best described as amphitheater-headed (pl. 2 and fig. 2, D). Most of the larger islands, except those veneered with more recent lava, are incised by valleys of this type. Several factors are concerned in the development of amphitheater-headed valleys.

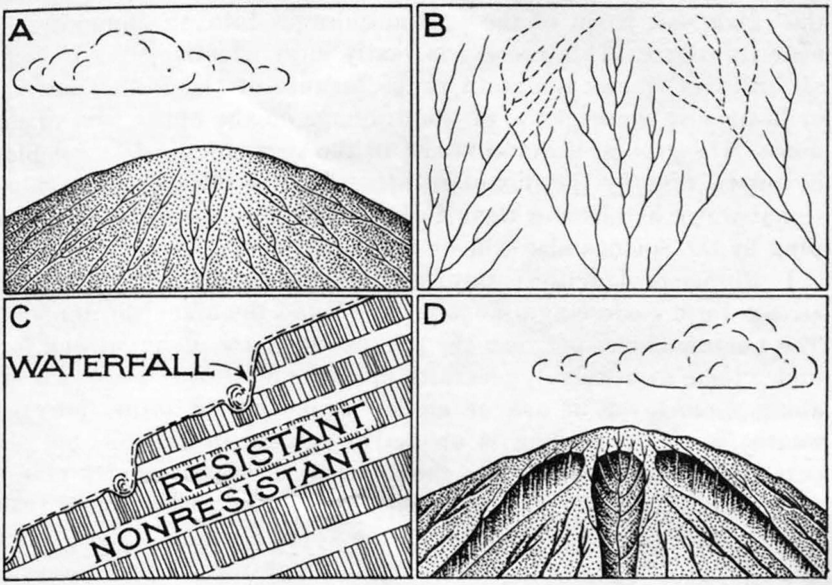


Figure 2. Diagram illustrating the formation of amphitheater-headed valleys. A. Youthful dome with radial drainage. B. Details of stream piracy that lead to a master stream, the precursor of an amphitheater-headed valley. C. Waterfalls caused by alternating resistant and nonresistant beds of basalt. D. Dome with amphitheater-headed valleys formed by the master streams.

1. Original slope of the surface: Streams that flowed originally on slopes of about 3° or less have not developed amphitheater-headed canyons; those that flowed on steeper slopes have developed amphitheaters; for example, Manoa Stream on Oahu. The original slope seems to be the most fundamental influence contributing to the formation of these valleys.

2. Alternate resistant and nonresistant beds, usually dipping downstream (fig. 2, C): The nonresistant clinker beds are undercut beneath the resistant layers of dense basalt and form waterfalls as they are cut back. Such falls increase in height as they follow the dip upstream and tend to coalesce into one high fall. Most of the streams have a "fall point," above which the stream actively incises

its canyon in the bedrock and below which the stream cuts laterally; for example, Haiku Stream, Oahu, has a 3.8 percent gradient below the fall point and an 88 percent gradient above the point (dropping 1,500 feet in a horizontal distance of 1,700 feet).

3. Rainfall and stream capture: The streams flowing more or less radially from the center of the dome are spaced relatively far apart in the region of low altitudes and low rainfall (fig. 2, A). With increasing altitude and rainfall, streams increase in number for a unit area, and stream capture becomes dominant (fig. 2, B). Thus, the catchment basin of the stream enlarges into an amphitheater near its source. This process is vastly more effective than it is on an ordinary linear mountain range because of the radial pattern, or headward convergence, of the drainage on the upper part of the dome. The ground water confined in the rocks of the dike complex is tapped first by the dominant streams, and this perennial additional water accelerates their ability to capture new streams. Sapping by the springs also widens the amphitheater.

4. Plunge-pool action: Captured tributaries entering a master stream form coalescing plunge pools around the amphitheater wall. The narrow ridges between the plunge pools are undercut and fail under their own weight, generally breaking off during heavy storms along some layer of ash or cinder weakened by saturation and weathering. Landsliding is an active process in Hawaii, but the scars are overlooked because they become covered so quickly with vegetation. After the "kona" (southerly) storm in November 1930, 14 new landslides were counted in the upper Nuuanu Valley, Oahu. Streams of low gradient do not develop high waterfalls and consequently cannot form plunge pools large enough to undermine the divides at the fall point.

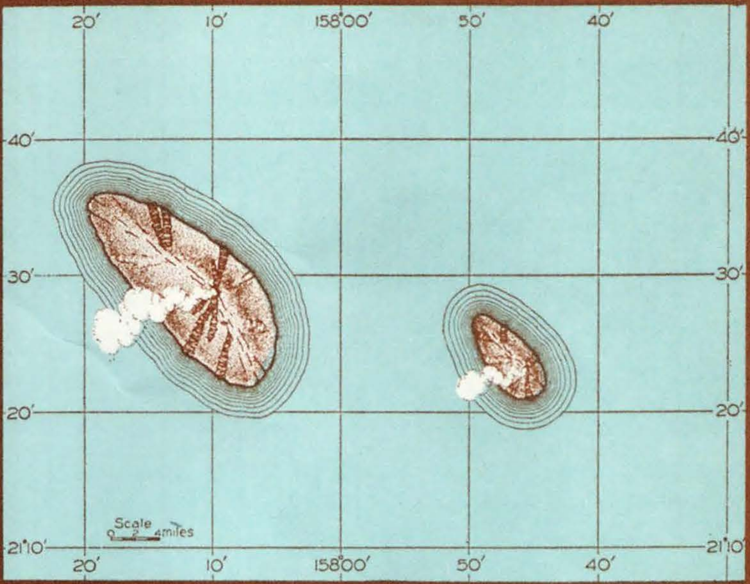
5. Cliff-forming rocks: Rocks must be competent to stand in vertical or nearly vertical walls. Basalt readily stands in high cliffs. Vertical jointing common in basalts is a contributing factor to sheer walls. If rocks are weak, the sheer amphitheater walls cannot develop at the head of a valley.

6. Inclination of the bedding: The attitude of the beds is probably important, but in Hawaii where strata rarely dip steeply, the part played by this factor cannot readily be determined. Steeply dipping beds, however, probably might not form sheer walls.

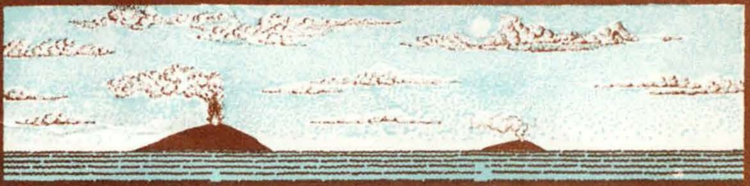
Following overgrazing and deforestation, the wind has eroded large quantities of lateritic soil from some of the islands. Kahoolawe and Lanai are notable examples. Wind erosion affects localities where more than 100 inches of rain falls annually if the surface becomes bare through landslides or other causes. In the Kau District, Hawaii, ash deposits are 50 feet or more in thickness. Dust blown from the ash-covered Kau Desert on Kilauea constitutes an

DIAGRAMS SHOWING THE GROWTH OF OAHU

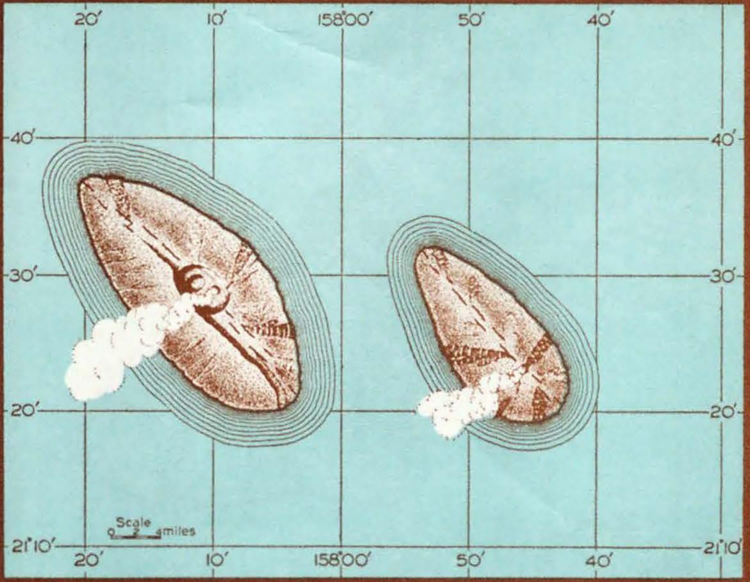
PLATE 3.



A. First stage showing the youthful Waianae (left) and Koolau (right) Volcanoes, each building lava domes over three rift systems intersecting at a central vent.

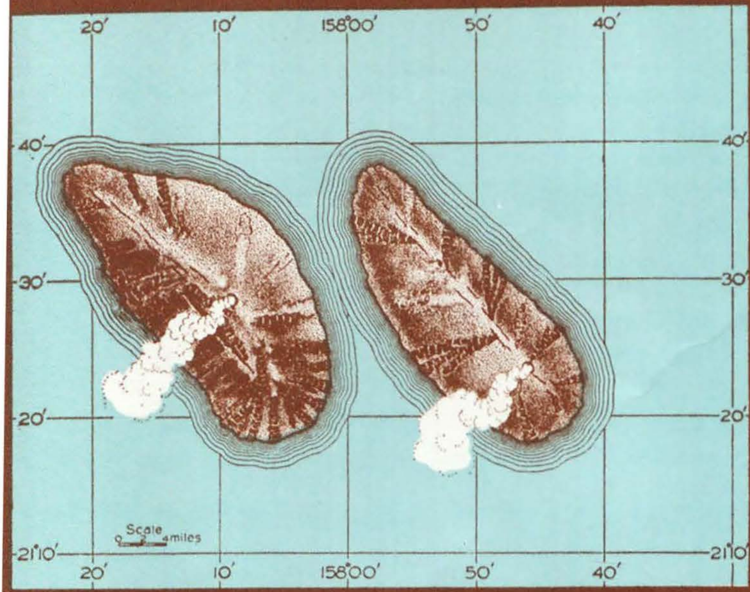


B. Silhouette of the first stage.



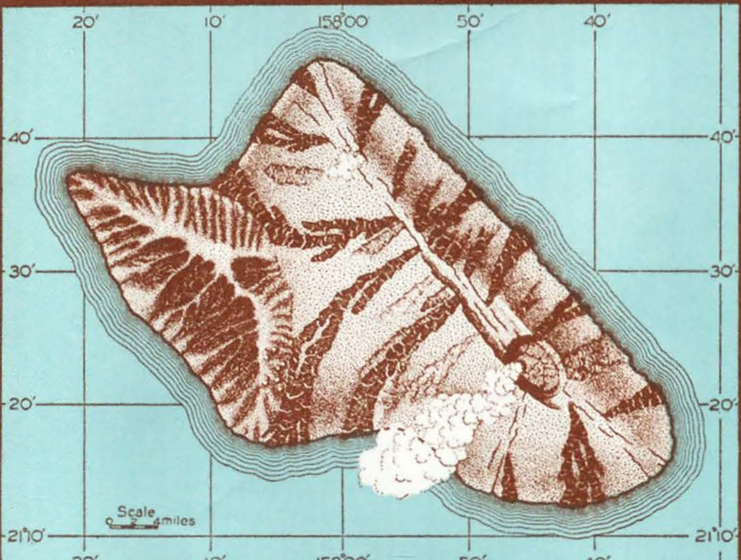
C. Second stage showing collapse or mature phase of the Waianae Volcano (left). A large caldera indents the summit and a high fault cliff prevents lava from flooding the newly established stream pattern on the southwest slope. The Koolau Volcano (right) is still in its youthful phase.

PLATE 4. DIAGRAMS SHOWING THE GROWTH OF OAHU



A. Third stage showing the Waianae Volcano (left) in the old age phase with the caldera practically filled and lava flows overtopping the northwest end of the fault cliff and plastering a few valleys on the southwest slope. The Koolau Volcano is building chiefly along the northwest rift.

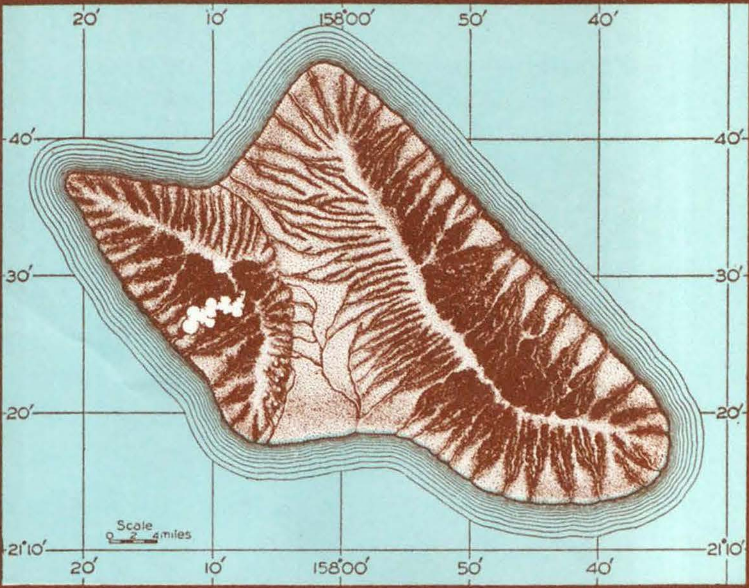
B. Silhouette of the fourth stage.



C. Fourth stage showing the Koolau Volcano (right) in its mature or collapse phase with a large caldera at its summit. The Koolau and Waianae Volcanoes are joined to form a single island. The amount of downfaulting along the northwest rift of the Koolau Volcano is unknown.

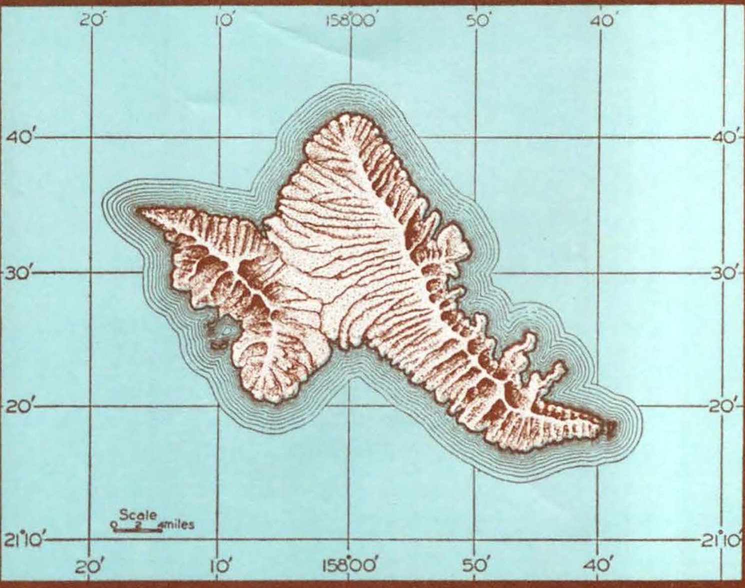
DIAGRAMS SHOWING THE GROWTH OF OAHU

PLATE 5.



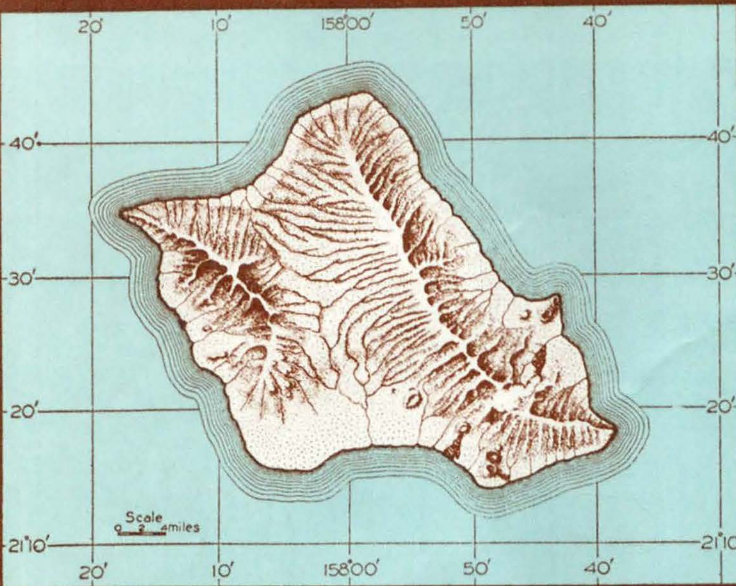
A. Fifth stage showing the Waianae (left) and the Koolau (right) Volcanoes deeply dissected by stream erosion. A small secondary cone erupts on the Waianae Range.

B. Silhouette of the sixth stage.

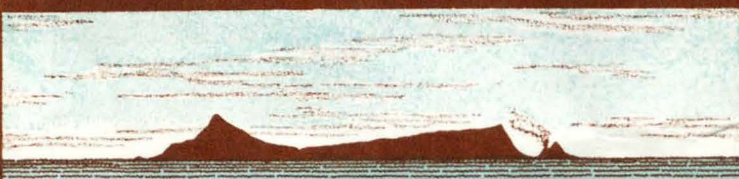


C. Sixth stage showing the Waianae (left) and Koolau (right) Ranges deeply submerged. The shore line is about 250 feet above the present sea level.

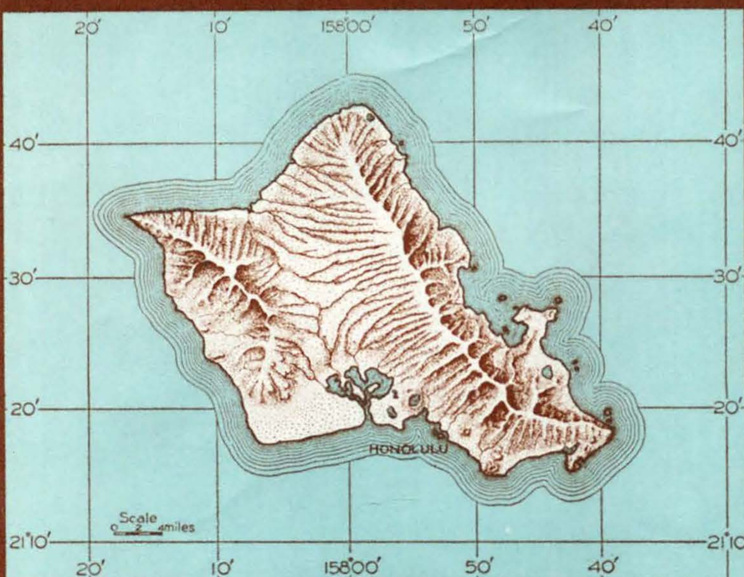
PLATE 6. DIAGRAMS SHOWING THE GROWTH OF OAHU



A. Seventh stage showing the Waipio stand of the sea (about 60 feet lower than the present). Numerous secondary eruptions have occurred on the Koolau Range (right).



B. Silhouette of the seventh stage.



C. Eighth stage showing the submergence of Oahu to present sea level.

appreciable part of these deposits. On Oahu, Maui, Molokai, Kauai, Lanai, and Niihau, dunes composed of calcareous beach sand and reaching heights of 100 feet, have drifted far inland. Most of the dunes are of late Pleistocene age and migrated inland when sea level was lower than at present. Some are now thoroughly lithified.

Marine erosion is most effective on the northeast or trade-wind coasts where sea cliffs nearly 3,000 feet have been cut. Because many of the severest storms come from the south and southwest, however, the coasts facing these directions—where not veneered by recent lava flows and not sheltered by other islands—also have high sea cliffs, some of which are 1,000 feet or more in height. Some sea cliffs have been retarded in their development by lava flows that have been eroded away (fig. 3). The sea cliffs generally plunge into deep

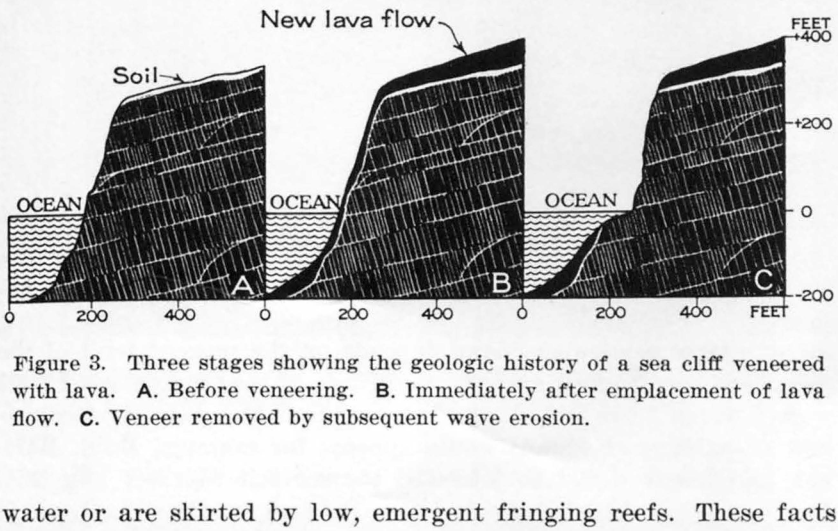


Figure 3. Three stages showing the geologic history of a sea cliff veneered with lava. A. Before veneering. B. Immediately after emplacement of lava flow. C. Veneer removed by subsequent wave erosion.

water or are skirted by low, emergent fringing reefs. These facts indicate that the cliffs were cut when the sea stood lower than at present, possibly during glacial epochs when the temperature of the surrounding ocean may have been too cold for corals to build fringing reefs. The high cliffs and great valleys have been cut simultaneously.

As a result of submergence, all the large valleys are partly drowned. Drilling on Oahu indicates that submergence exceeded 1,200 feet. On Lanai, fossiliferous marine sediments 1,070 feet above sea level and excellent beach deposits at 560 feet are demonstrable proof of large emergence. A complicated history of emergences and submergences in Pleistocene time is shown by the geologic work now accomplished. Ancient shore lines determined so far are listed with the youngest at the top.

Ancient shore lines in the Hawaiian Islands *

Approximate altitude (feet)	Name of terrace	Approximate altitude (feet)	Name of terrace
0	Present	—300±	Kahipa
5	Kapapa	55	Kahuku
[a]25	Waimanalo	260±	Olowalu
—60±	Waipio	560	Manele
45	Waialae	1,200±	Mahana
70	Laie	—1,200±	Lualualai
95	Kaena		

[a] Two shore lines 22 and 27 feet above mean sea level.

As far as is known, all terraces younger than the 260-foot halt are concordant, indicating that the shore lines are eustatic. These strand lines developed because of changing ocean level which, in turn, depended upon either changes in the volume of the polar icecaps, or changes in the configuration of the ocean floor, or upon both these causes combined. Possibly the older strands can be attributed to isostatic adjustment following the transfer underground of large volumes of magma or to preglacial eustatic movements.[3] This subject, however, awaits additional study.

Even though only a few miles apart, each volcano in the Hawaiian Islands was built seemingly over a practically independent magma reservoir; each has an erosional history peculiar to its height and form; and each differs somewhat in age from the others. Volcanoes on adjacent islands may have a more closely related history than those on the same island, because the number of volcanoes incorporated in any particular island depends on the present level of the ocean and is, therefore, entirely fortuitous. If the present ocean level were lowered 2,000 feet, an entirely different grouping of volcanoes and assemblage of islands would appear; for example, Maui, Molokai, and Lanai would be joined if the sea fell 250 feet (fig. 26). Because of individual characteristics, the geology of each volcano is given briefly in the following pages. For convenience in locating, volcanoes are discussed under the name of the island.

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[3] Stearns, H. T., Eustatic shore lines in the Pacific: Geol. Soc. America Bull., vol. 56, pp. 1071–1078, 1945.

*See Supplement for revision of this table.

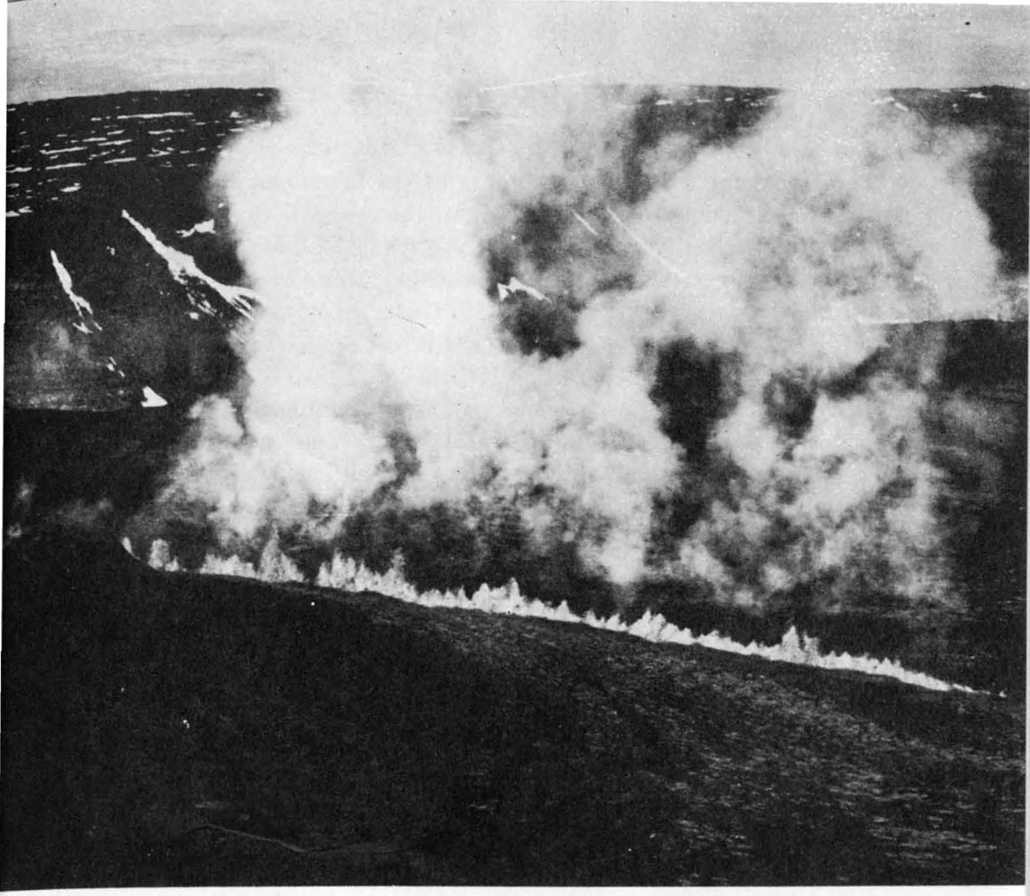
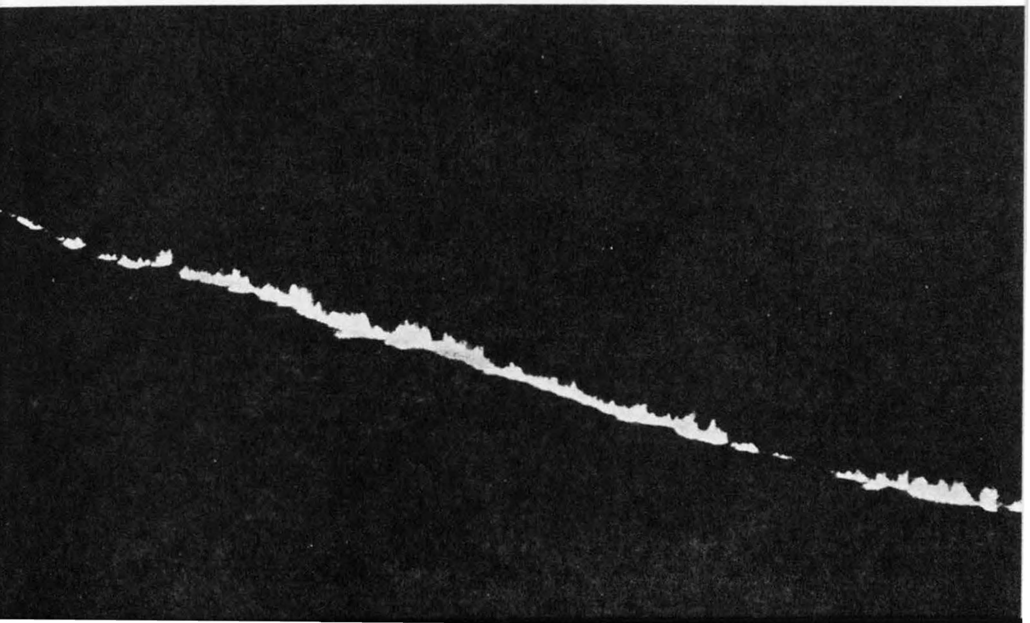


Plate 7A. "Curtain of fire" formed by coalescing lava fountains along fissure on the floor of Mokuaweoweo Caldera, April 8, 1940.

Plate 7B. "Curtain of fire" on the night of April 8, 1940. Photos by U.S.A.A.F.



GEOLOGY

GENERAL STATEMENT

The Hawaiian Islands are a chain of shield-shaped basaltic domes built over a fissure 1,600 miles long in the ocean floor. This tectonic feature has existed probably since at least Middle Tertiary; but it is not known whether the fissure is a tear along the crest of a fold, a simple tension crack, a group of echelon faults bounding a raised block, or a strike-slip fault.[4] The lava now rises along tension cracks bounding lozenge-shaped blocks strung out linearly from southeast to northwest. The vents are spaced about 25 miles apart.

Exposed parts of the domes contain by volume less than one-half of 1 percent of explosive debris, thus indicating the dominance of lava outpourings. The flows range from a few inches to 900 feet in thickness, but most of them are from 10 to 30 feet. Phreatic and phreatomagmatic explosions have occurred sparingly.

The main bulk of the domes consists of lava beds dipping 3° to 20° away from their source and rarely separated even by thin soil beds, thereby indicating rapid accumulation of flows such as is taking place now on Mauna Loa Volcano, Hawaii. Thin soils between the flows in some volcanoes, show that the time interval separating eruptions lengthened toward the close of the dome-building epoch. Many of these soil beds are decomposed vitric tuff which, during the early phase of eruption, generally is deposited in small quantities by lava fountains at the vents.

Fissure eruptions characterize Hawaiian volcanoes. The usual eruption is preceded by a few slight earthquakes as the ground opens to allow the exit of the magma. These fissures are a few inches to a few feet wide, and during the rapid dome-building epoch are limited to definite rift zones (pl. 1). The widest single dike known in Hawaii is 40 feet across, but the average width is about 2 feet. Eruptions often begin with a lava fountain which is caused by frothing at the top of the lava column when pressure on the enclosed gases is released (pl. 7). If effervescence is slight, a line of spatter cones 5 to 50 feet high is built; if voluminous, a line of cinder cones 50 to 300 feet high results. Rivers of pahoehoe pour from the fissure; but as it flows down the mountainside, the lava usually changes to aa. Some of the lava flows entering the sea disrupt violently and build fragmental cones. Recorded eruptions have lasted from a few hours to 10 months, and the flows have ranged in length from a few feet to 35 miles. The discharge of juvenile water increases in direct proportion to the amount of effervescence. Profiles of typical cognate secondary cones superimposed on the great lava domes are shown in figure 4.

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[4] Betz, F. and Hess, H. H., The floor of the North Pacific Ocean: Geogr. Rev., vol. 32, p. 111, 1942.

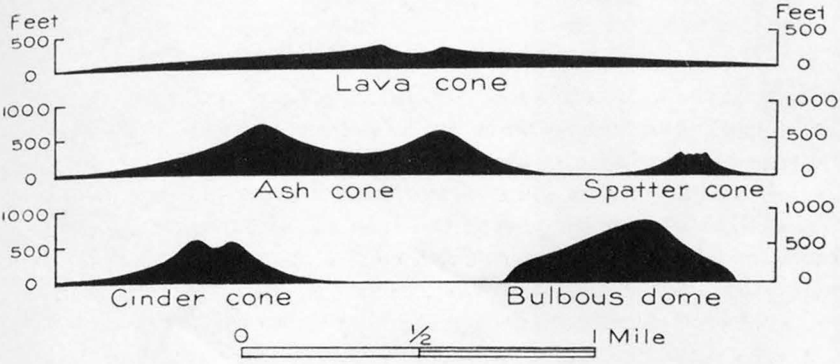

Figure 4. Profiles of cognate secondary cones. Ash cones after consolidation are called tuff cones.

Increased knowledge regarding the geology of the islands seems to indicate that all Hawaiian volcanoes pass through the following more or less similar stages in development (fig. 5).

Stage 1.—Building of a volcano from the ocean floor to sea level. During this submarine phase, the volcano in development probably lays down chiefly pillow lavas and produces large quantities of ash and pumice as a result of the contact of the magma with sea water. When a cone first rises above sea level, it is composed largely of weakly consolidated ash which is rapidly eroded by the sea. Shortly afterward, lava flows veneer the cone, and the erosive effectiveness of wave action is greatly decreased.

Stage 2.—Once the cone is above sea level, thin sheets of highly fluid primitive-type olivine basalts are rapidly poured out usually from one minor and two major rifts as well as from a small crater at their intersection. Eventually a shield-shaped dome is built. In the dominantly olivine-bearing basalts, small feldspar phenocrysts are common and pyroxene phenocrysts are scarce. Cinder cones seldom form. Usually a vent is either a fissure bordered by low spatter heaps or an opening concealed by a flat mound of pahoehoe. A few thin beds of lithic and vitric tuff may be deposited. Because the surface is highly porous and the time interval between eruptions is short, stream erosion is nonexistent. All Hawaiian volcanoes have passed through this youthful stage.

Stage 3.—The volcano gradually collapses over the vent areas to form a caldera on the summit (pl. 8) and shallow grabens along the major rifts. The composition of the lavas does not change appreciably, nor does the time interval between eruptions lengthen. Lavas ponded in closed fault basins are very massive, however, and in physical appearance differ greatly from the pre-caldera lavas. When eroded they form sheer cliffs which usually show columnar struc-

Opposite page: Plate 8. Summit of Mauna Loa Volcano showing Mokuaweoweo Caldera and the pit craters on the southwest rift after a flurry of snow. Mauna Kea in the background. Photo by U.S.A.A.F.

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ture. Lithic and vitric tuff beds may be developed more frequently than in the first phase. The highest wall of the caldera usually bounds a segment between the two rift zones which intersect at an obtuse angle. Generally the seaward slope of this high wall ceases to be flooded with lavas; and as a result, canyons are eroded into it, while flows continue to veneer the other slopes. Sea cliffs are another characteristic feature of the high-walled slope. Two distinct physiographic stages may exist, therefore, on the same volcano.

Mauna Loa, Kilauea, and Lanai are now in this volcanic phase. The other domes have passed through this stage. The West Molokai dome adjacent to the summit collapsed but apparently a caldera did not form.

Stage 4.—When the volume of the lavas poured out exceeds the amount of the collapse, the caldera and grabens are partly or entirely obliterated. Time intervals between eruptions grow progressively longer, and the composition of the lavas may change slowly or abruptly to more feldspathic types. Trachyte, andesite, or closely related rocks are laid down in thick sheets, chiefly as aa flows. In this phase, the more highly ferromagnesian lavas usually contain large phenocrysts of one or all the following minerals: pyroxene, olivine, and feldspar. Peridotitic and gabbroic cognate inclusions are common. High lava fountains which build large cinder cones characterize most eruptions, and bulbous domes may be formed (fig. 6). Vitric tuff beds increase in number and thickness. The profile of the dome steepens and becomes studded with cones. Some of the vents lie outside of the rift zones. Erosion has resulted in local unconformities between some of the flows. Hualalai, Mauna Kea, and Kohala domes are in this phase.

Volcanoes passing through this phase take either of two courses. One is the course followed by West Maui, Kohala, and East Molokai in which the primitive olivine basalts are succeeded by (1) a thin incomplete veneer of olivine porphyritic basalts usually carrying augite phenocrysts, (2) a relatively short pause, and (3) eruptions of oligoclase andesites and trachytes which form an incomplete veneer and add only a few hundred feet of lava to the summit of the volcano. The second is the course followed by Haleakala and Mauna Kea in which no inactive period occurs, trachytes and oligoclase andesites are rare or absent, and andesine andesites dominate but are interbedded with both olivine basalts and picrite basalts carrying large augite phenocrysts. These lavas may add several thousand feet to the height of the volcano.

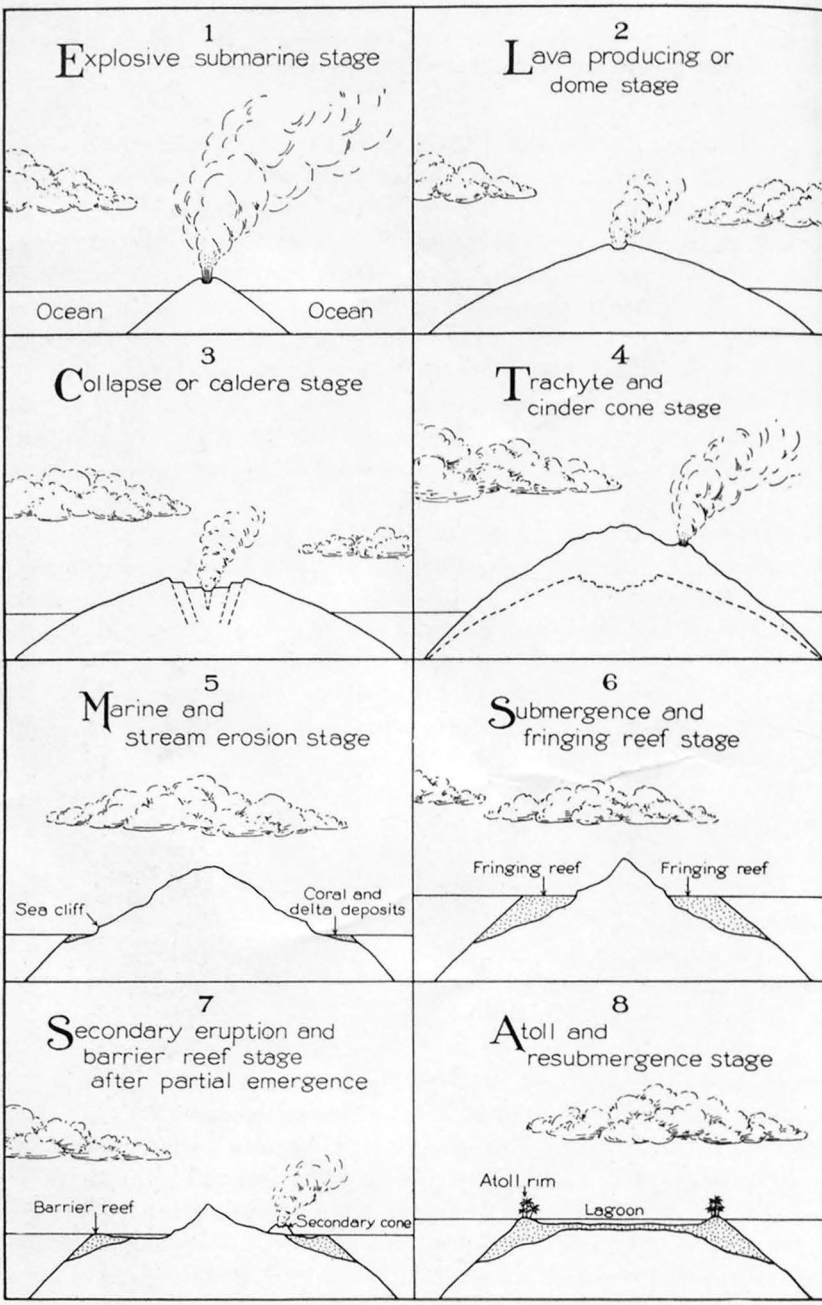


Figure 5. Eight stages in the geologic history of a volcanic island in the central Pacific.

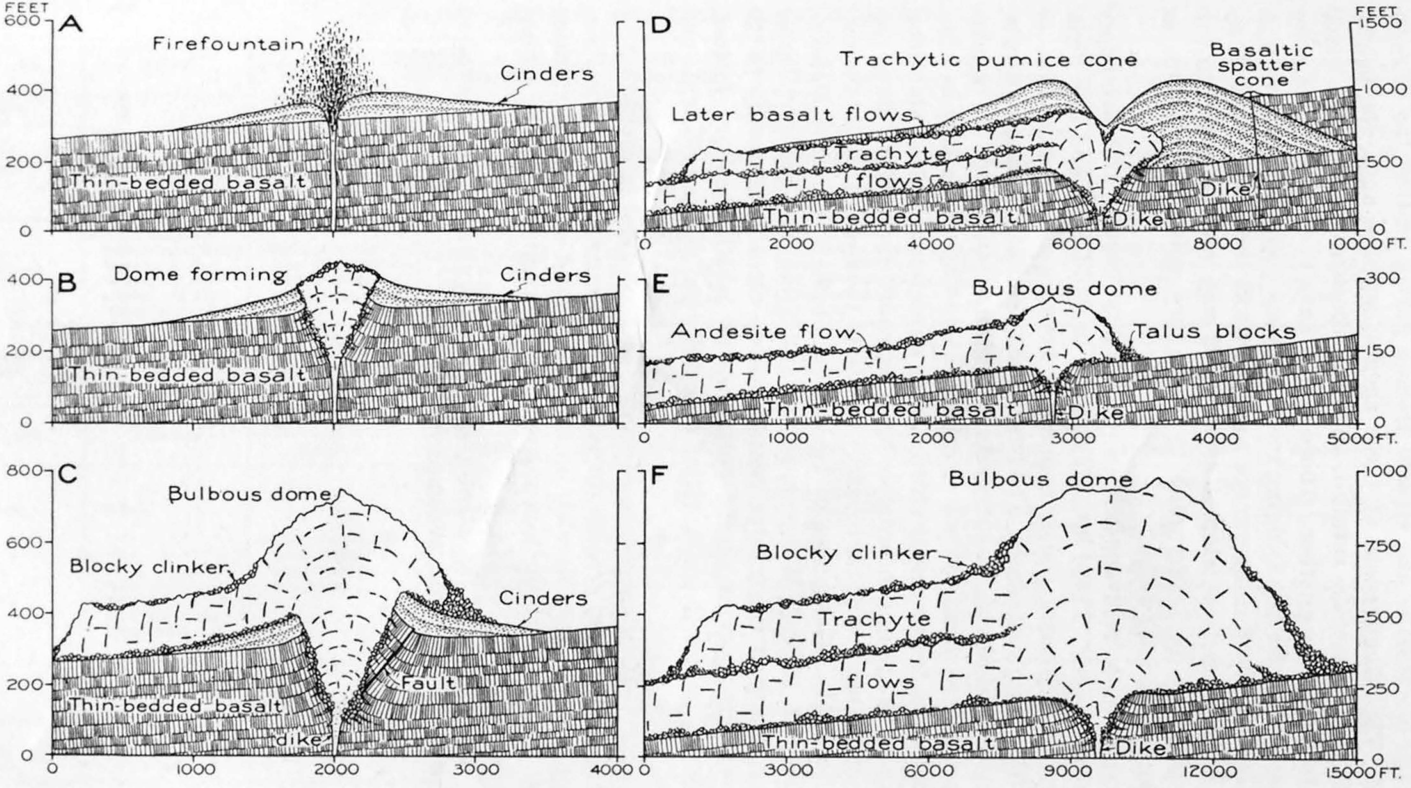


Figure 6. Sections of typical bulbous domes. **A** to **C** shows formation of common bulbous dome underlain with cinders. **D**. Puu Waawaa, Hawaii. **E**. Andesite dome and flow. **F**. Trachyte bulbous dome and flow.

Stage 5.—Marine and stream erosion partly destroy the volcanic dome. The effectiveness of these agents depends upon the height, which determines the rainfall, and the exposure, whether the island lies to the lee of another. Those which have been in this stage for a long period develop fringing reefs, high sea cliffs, and deep valleys.

Stage 6.—Deep submergence partly drowns the islands and extensive fringing reefs develop. Barrier reefs may develop or the growth of coral may be interrupted by secondary volcanic eruptions as shown in the next stage.

Stage 7.—A rejuvenation of volcanicity occurs and secondary eruptions occur. These lavas, extruded in middle(?) and late Pleistocene and Recent times, commonly contain either nepheline or melilite or both minerals. The basalts may contain or lack pyroxene, feldspar, and olivine phenocrysts. Peridotitic and gabbroic cognate inclusions are usual. Vitric or crystal-lithic-vitric tuffs may be widespread. The latter result chiefly from phreatomagmatic explosions. These lavas are unconformable upon extruded rocks of all three preceding phases, a fact that clearly points to the intervention of a long erosion cycle. The domes of Haleakala, West Maui, East Molokai, Kahoolawe, Koolau, Waianae, Kauai, and Niihau are in this volcanic phase. Many of these later vents show no close relationship to the ancient rift systems of the volcanoes on which they are formed. Many lie on north-south rifts, especially on Niihau, Kauai, and Oahu.

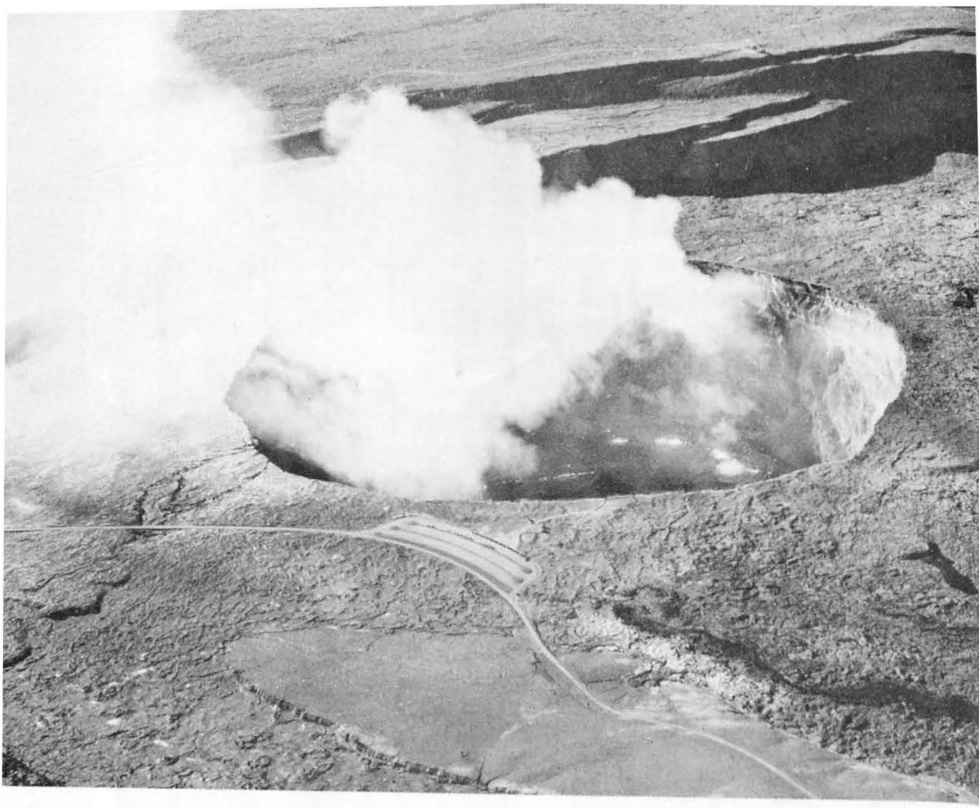
Stage 8.—If submergence continues or the island is planed off by marine and stream erosion during the fluctuating seas of the Pleistocene an atoll may develop on the eroded and submerged volcanic mass. The atolls in the leeward part of the archipelago were formed in this manner.

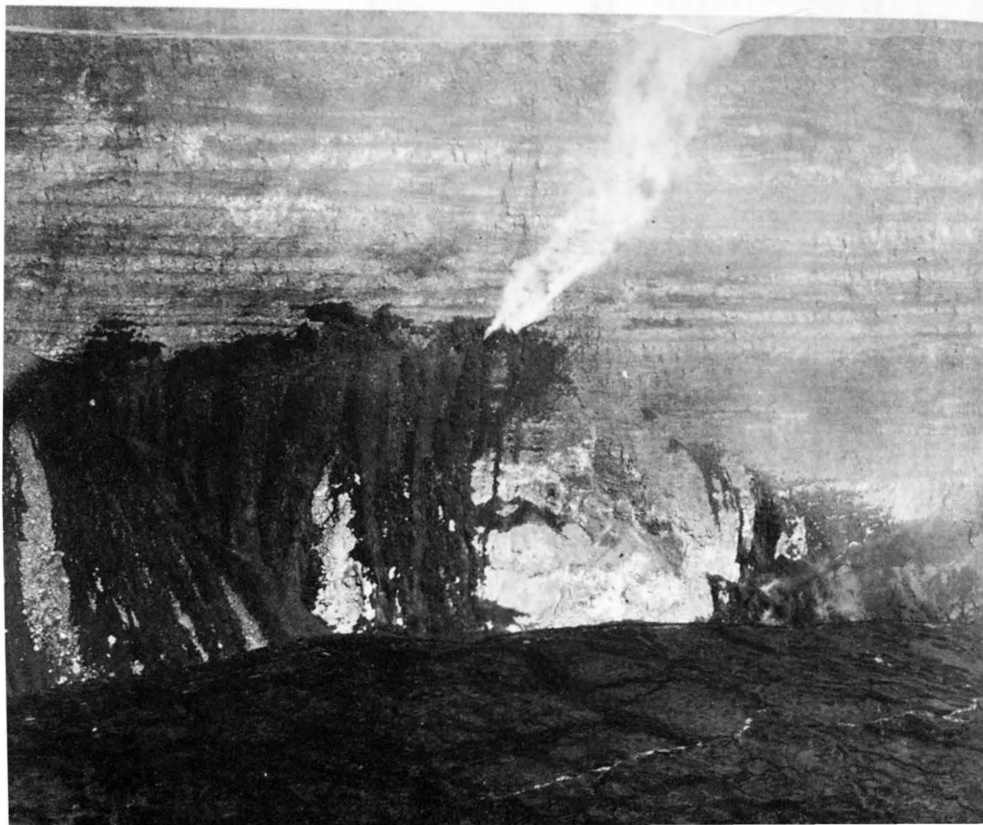
A correlation of the stratigraphic rock units in the Hawaiian Islands is given in the accompanying table.

Stratigraphic rock units in the Hawaiian Islands

Age	Niihau	Kauai		Oahu		Molokai		Lanai
		Kauai Mountain	Hoary Head	Waianae Range	Koolau Range	West Molokai	East Molokai	
Historic				Coral fill	Coral fill			
Recent	Younger alluvium, playa deposits, and unconsolidated calcareous beach and dune sand	Younger alluvium, unconsolidated calcareous beach and dune deposits, and younger rocks of the Koloa volcanic series	Younger alluvium and unconsolidated calcareous beach and dune deposits	Younger alluvium and unconsolidated calcareous beach and dune deposits	Younger alluvium, unconsolidated beach and dune deposits, and younger rocks in the Honolulu volcanic series	Younger alluvium and unconsolidated calcareous beach and dune deposits	Younger alluvium and unconsolidated calcareous beach deposits	Younger alluvium and unconsolidated calcareous beach and dune deposits
Local unconformity								
Pleistocene	Lithified calcareous dunes, emerged marine limestone, dunes of volcanic sand, older alluvium, and Kiekie volcanic series	Lithified calcareous dunes, older alluvium, and older rocks of the Koloa volcanic series	Lithified calcareous dunes and older alluvium	Lithified calcareous dunes, emerged marine limestone, older alluvium, and Kolekole volcanics	Lithified calcareous dunes, emerged marine limestone, older alluvium, and older rocks in the Honolulu volcanic series	Lithified calcareous dunes and older alluvium	Emerged marine limestone, older alluvium, Kalaupapa basalt, and Mokuhooniki tuff	Lithified calcareous dunes, emerged marine limestone, and older alluvium
Great erosional unconformity								
Pliocene and older	Paniau volcanic series	Waimea volcanic series; caldera-filling (upper) and extra-caldera (lower) members	Haupu volcanic series; caldera-filling and extra-caldera members	Waianae volcanic series; upper, lower, and middle members	Koolau and Kailua volcanic series	W. Molokai volcanic series	E. Molokai volcanic series; upper, lower, and caldera complex members	Lanai volcanic series

Age	Kahoolawe	Maui		Hawaii				
		West Maui	East Maui	Kohala Mountain	Mauna Loa Volcano	Mauna Kea	Hualalai Volcano	Kilauea Volcano
Historic	Red loess	Younger alluvium and unconsolidated calcareous beach and dune deposits	Volcanics of 1750 (?)	Younger alluvium, unconsolidated calcareous beach deposits, and black sand dunes	Historic member of the Kau volcanic series and mudflow of 1868	Younger alluvium, unconsolidated calcareous beach deposits, volcanic sand dunes, vitric ash deposits, and upper member of the Laupahoehoe volcanic series	Historic member of the Hualalai volcanic series. (Volcanics of 1800–01)	Historic member of the Puna volcanic series
Recent	Younger alluvium, unconsolidated calcareous beach deposits and late volcanics		Younger alluvium, unconsolidated beach and dune deposits, and younger rocks in the Hana volcanic series		Black sand dunes, and the prehistoric member of the Kau volcanic series		Unconsolidated calcareous beach deposits, and younger rocks of the prehistoric member of the Hualalai volcanic series	Black sand dunes, and prehistoric member of the Puna volcanic series
Local unconformity								
Pleistocene	Older alluvium	Emerged marine limestone, older alluvium, and Lahaina volcanic series	Kaupo mudflow, older alluvium, and older rocks in the Hana volcanic series including the Kipahulu member	Older alluvium, Pahala ash, and Hawi volcanic series	Pahala ash and Kahuku volcanic series	Glacial deposits, older alluvium, lower member of the Laupahoehoe volcanic series, Pahala ash, and younger rocks in the Hamakua volcanic series	Pahala ash and older rocks of the Hualalai volcanic series including the Waawaa volcanics	Pahala ash and Hilina volcanic series
Pliocene and older	Kanapou volcanic series; caldera and extra caldera members	Honolua volcanic series Wailuku volcanic series	Kula volcanic series Honomanu volcanic series	Pololu volcanic series	Ninole volcanic series	Older unexposed rocks in the Hamakua volcanic series	Probably deep unexposed rocks in the Hualalai volcanic series	





Opposite page, top: Plate 9A. Halemaumau in eruption, September 6, 1934.

Bottom: Plate 9B. Lava cascade 400 feet high on wall of Halemaumau, September 7, 1934. Photos by U.S.A.A.F.

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ISLAND OF HAWAII

The island of Hawaii consists of five volcanoes, namely, Mauna Kea (13,784 feet), Mauna Loa (13,679 feet), Hualalai (8,251 feet), Kohala (5,505 feet), and Kilauea (4,040 feet) (pl. 9). Figure 7 is a map of Hawaii showing the historic lava flows.

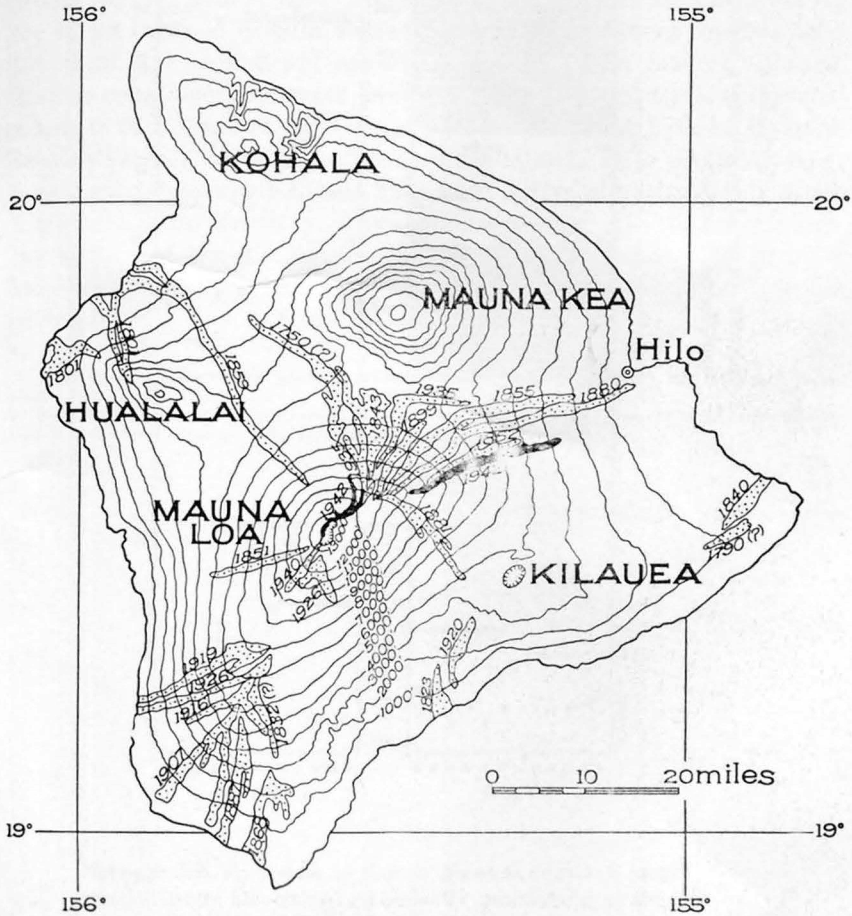

Figure 7. Map of Hawaii showing historic lava flows. After G. A. Macdonald.

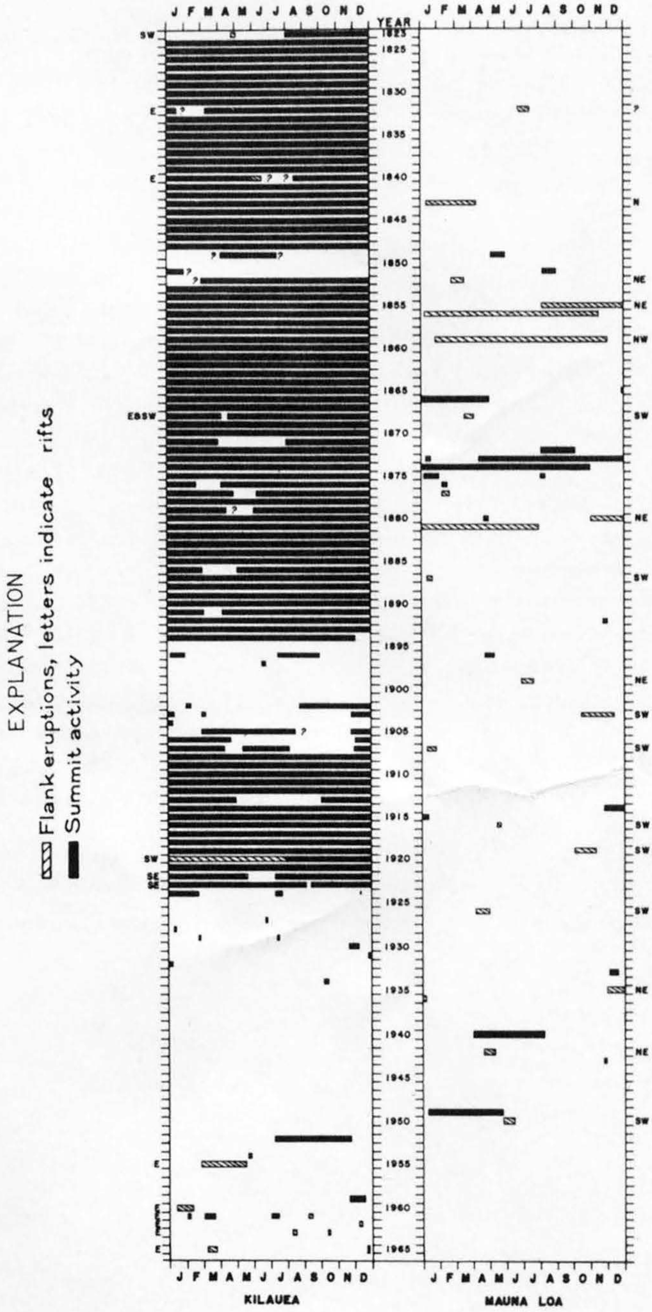

Figure 8. Graph showing periods of activity of Kilauea and Mauna Loa volcanoes. (Revised by Macdonald and Hubbard, Volcanoes of the National Parks in Hawaii, 1965.)

During the past century Mauna Loa has averaged one outbreak in the caldera for every 3⅓ years, and has produced a lava flow every 6 years.[5] Kilauea has contained a lava lake for years at a time, but since 1800 has produced only seven flows outside of its caldera (fig. 8). The only recorded eruption of Hualalai was in 1800–1801. Mauna Kea and Kohala have not erupted in historic time.

Hawaii, except for the windward slope of Kohala is little dissected. The only perennial streams are on the northeastern slopes of Mauna Kea and Kohala. The high permeability of the fresh lavas forming the surface of Kilauea, Mauna Loa, and Hualalai inhibit the development of permanent streams. Large areas on these mountains are covered with black rock and are bare and devoid of vegetation. The southwestern side of Kilauea is a desert.

The lavas of Mauna Loa interfinger with the lavas of Kilauea, Hualalai, and Mauna Kea. The lavas of Mauna Kea interfinger with the latest lavas of Kohala Mountain. The 25-foot shore line has been found on Mauna Kea but not on Hualalai, Mauna Loa, or Kilauea. Marine conglomerates reach a height of 260 feet and stream terraces, a height of 1,100 feet on Kohala Mountain. Thus, Kohala Volcano became extinct before all others on the island. It is probable, however, that all except Kilauea have been active simultaneously since some time in the Tertiary. The stratigraphy given in the accompanying table and the distribution of the rock units shown in figure 9 have been recently completed.[6] The mountains are described in order of height.

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[5] Jaggar, T. A., Hawaiian Volcano Research Assoc., Volcano Letter, no. 443, p. 1, Jan. 1937.

[6] Stearns, H. T., and Macdonald, G. A., Geology and ground-water resources of the Island of Hawaii: Hawaii Div. Hydrography, Bull. 9 (in press).

Stratigraphic rock units in the island of Hawaii

(The volcanic rocks of Mauna Loa, Mauna Kea, and Hualalai, those of Mauna Kea and Kohala, and those of Mauna Loa and Kilauea interfinger)

Age	Hualalai	Kohala Mountain	Mauna Loa		Kilauea	Mauna Kea	
Historic	Historic member of the Hualalai volcanic series (1800–01)	Unconsolidated alluvium, dunes and landslides	Historic member of the Kau volcanic series (1832–1942)	Mud flow of 1868	Historic member of the Puna volcanic series (1790–1934)		Ribbons of gravel and small alluvial fans
Recent	Prehistoric member of the Hualalai volcanic series		Dunes		Dunes	Upper member of the Laupahoehoe volcanic series	
Late Pleistocene		Fluvial conglomerates	Prehistoric member of the Kau volcanic series		Prehistoric member of the Puna volcanic series	Glacial debris and fluvial conglomerates Lower member of the Laupahoehoe volcanic series Local erosional unconformity	
	Pahala ash (exposed on Waawaa volcanics only)	Pahala ash (not differentiated)	Pahala ash		Pahala ash	Pahala ash	
Early and middle Pleistocene	Waawaa volcanics and lower unexposed part of Hualalai volcanic series	Fluvial conglomerates Hawi volcanic series	Kahuku volcanic series		Hilina volcanic series	Hamakua volcanic series	
Pliocene		Great erosional unconformity Pololu volcanic series	Great erosional unconformity Ninole volcanic series				

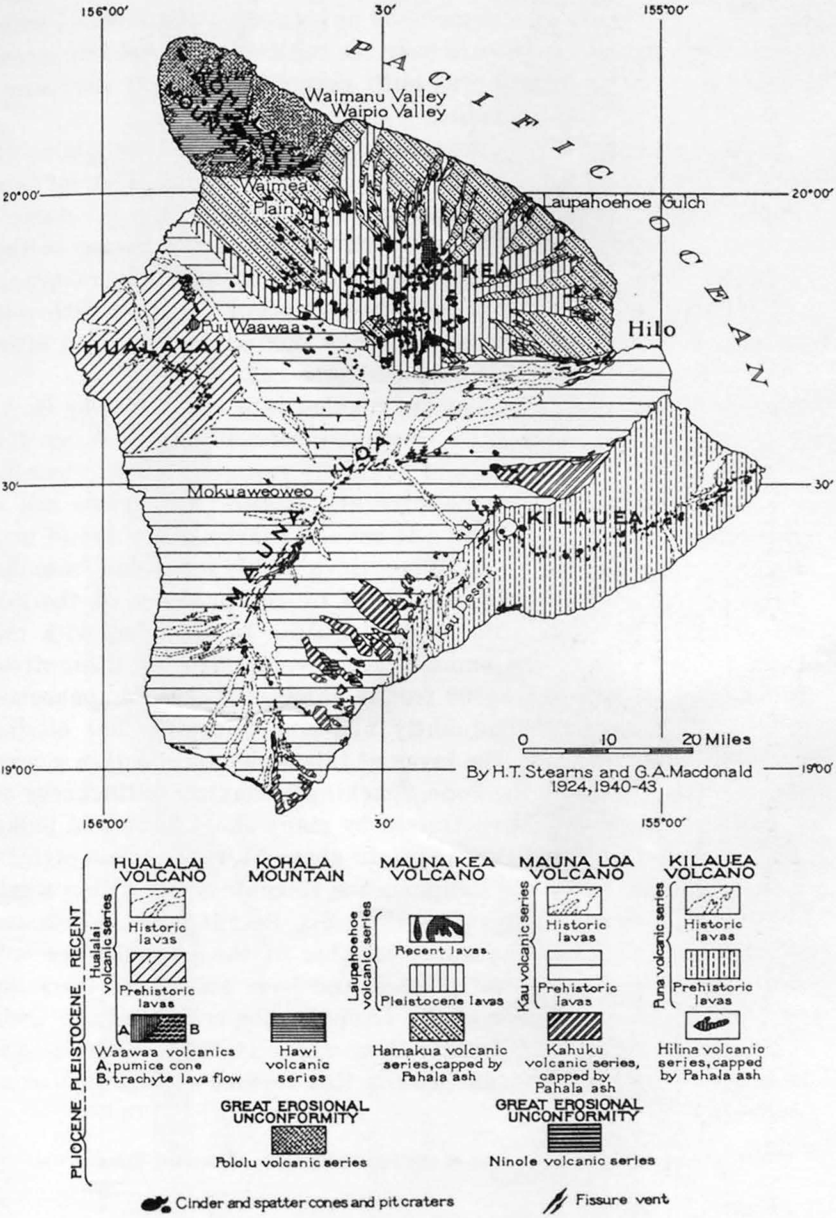

Figure 9. Geologic map of the island of Hawaii. Faults omitted.

MAUNA KEA.—This mountain is the highest insular peak on the earth (pl. 10). Snow usually remains throughout the year in one place on the summit. The dome is 30 miles across and studded with cinder cones, most of which are near the top and clustered into zones indicating that the volcano was built over rifts trending northeastward, southward, and westward.

The lower slopes of the mountain, especially the high plains of Waimea, are blanketed with tan-colored ash deposits. Most of this material is fine-grained firefountain debris wafted from the numerous cinder cones nearby.[7] Streams have cut narrow gashes in the windward slope and Laupahoehoe Gulch contains an intracanyon flow. At its mouth is a flat of pahoehoe so recent that very little soil has formed on it. Obviously Mauna Kea poured out this lava after a canyon more than 400 feet deep had been cut.

The volcanics of Mauna Kea are divided into two series by G. A. Macdonald. The older or the Hamakua volcanic series forms the major part of the mountain and is chiefly primitive olivine basalts with picrite-basalts carrying olivine and augite phenocrysts and a few andesites in its upper part. It usually carries a blanket of tan-colored vitric Pahala ash 4 to 15 feet thick and is separated from the overlying Laupahoehoe volcanic series by the presence of the ash blanket and the porphyritic picrite-basalts. Interbedded with the Hamakua lavas near the summit are several beds of lithic-vitric explosion breccias reaching 90 feet in thickness. The Laupahoehoe volcanic series are predominantly andesine andesites but olivine basalts are also present. The lavas of this series form a thin veneer over the upper part of the cone, reaching a maximum thickness at the summit. They are characterized by many short flows and bulky cinder cones. The top of the mountain above 11,000 feet is a plateau that may be caused by the Laupahoehoe volcanic series filling a caldera in the Hamakua volcanic series. Six Recent flows, which are all andesites, comprise the upper member of the Laupahoehoe volcanic series. They are mostly black and bare and differ from the lavas in the lower member of the Laupahoehoe series only in their youthful appearance and because those above 10,500 feet overlie glacial drift. They indicate that Mauna Kea became extinct in Recent time.

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[7] Wentworth, C. K., Ash formations of the Island Hawaii: Hawaiian Volcano Observatory, 3rd Spec. Rept., p. 57, 1938.

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Opposite page: Plate 10. View of summits of Mauna Kea and Mauna Loa volcanoes. Photo by U.S.A.A.F.

A glacier about 250 feet thick covered the top of the mountain during the Wisconsin glacial stage as shown by moraines and glaciated areas above 10,500 feet. The glacial evidence was discovered in 1909[8] and details have been described more recently.[9] Three older drifts have been described,[10] but these have been found to be fanglomerate and explosion deposits.[11]

MAUNA LOA.—Mauna Loa is a shield-shaped dome about 60 miles long and 30 miles wide (pl. 10). It is one of the most prolific lava producers on earth. A few cinder cones lie on its slopes and in the summit caldera, Mokuaweoweo. The caldera resulted from collapse and is growing broader through coalescence with adjacent pit craters (pl. 8). It is now about 19,500 feet long, 9,200 feet wide, and 600 feet deep. During recent years, lava, poured from fissures and cones on its floor and rim, has been filling the depressions, and a few weak explosions have occurred.[12]

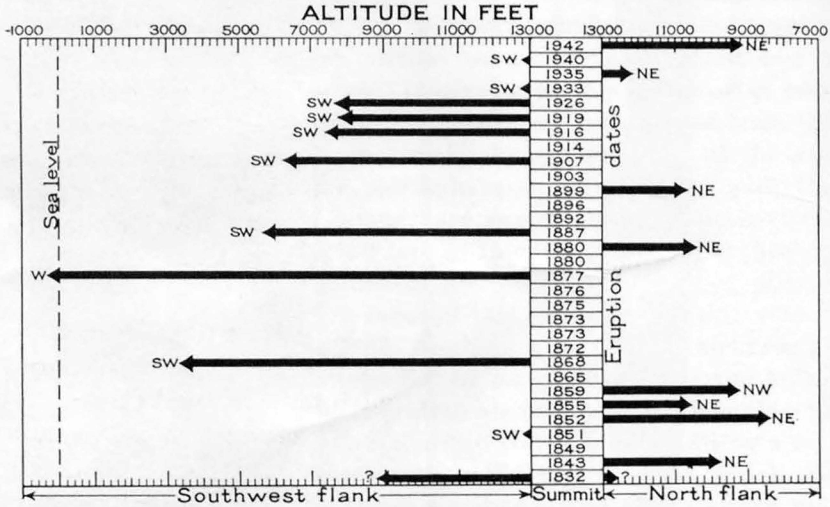

Figure 10. Graph showing the location and altitude of eruptions of Mauna Loa Volcano, 1832-1942.

Mauna Loa has well-defined southwest and northeast rift zones and a weakly developed north rift zone (pl. 1). Most eruptions start as high, short-lived lava fountains in the caldera, then change to outpourings of lava from vents at lower altitudes along the rifts. The location and altitude of the eruptions are shown in figure 10.

[8] Daly, R. A., Problems of the Pacific Islands: Am. Jour. Sci., 4th ser., vol. 41, p. 175, 1916. [9] Gregory, H. E. and Wentworth, C. K., General features and Glacial geology of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 48, pp. 1719–1742, Dec. 1, 1937. [10] Wentworth, C. K. and Powers, W. E., Multiple glaciation of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 52, pp. 1193–1218, Aug. 1941. [11] Stearns, H. T., Glaciation of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 56, pp. 267–274, 1945.

[12] Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, p. 153, 1930.

The southwest rift probably produces submarine flows also. The south and southeast sides of the volcano are broken by echelon faults arranged in two patterns. One distinguished by the northeasterly strike of the faults, is the most common. The other with radial faults is best developed in the southwest rift zone. Displacement along a few faults has occurred in historic time. Some of the scarps in the southeast slope reach heights of about 600 feet.

On the southeast slope, ash deposits, attaining a thickness of 55 feet, blanket the lower slopes of the mountain. The bed is composed of wind-blown dust from the ash deposits in the Kau Desert, ash from explosions at Kilauea,[13] and fine vitric material from cones on Mauna Loa and Mauna Kea.

A number of radial ridges project above the general slope of Mauna Loa in the southeast slope. The ridges are believed to represent divides between canyons several thousand feet deep which were eroded in Mauna Loa and later partly filled with lava flows.[14] Mauna Loa appears, therefore, to be an eroded mass probably as old as Kohala Mountain. The volcano may have been completely inactive during the erosion of the valleys, although a high fault escarpment might have bordered the summit caldera and for a long time shielded the district from lava flows. Because of the fairly high rainfall in the area and the originally steep gradients of the streams tumbling over fault escarpments, these canyons may have been cut in a relatively short time.

A typical eruption of Mauna Loa begins with a fume cloud rising several miles and lava fountains reaching heights of several hundred feet (pl. 11A). These fountains erupt from long cracks a few feet wide and eventually merge into veritable curtains of molten lava (pl. 7). At first they do not produce cones, but the descending lava flows away as frothy pahoehoe (pl. 11B). Some pumice falls close to the fountains, but most of it floats away on the lava stream, though small quantities of pumice and Pele's hair are blown away by the wind. Generally within a few days or a week, the fountains die down leaving spatter ramparts or chains of spatter and cinder cones along the fissures.

Usually great quantities of highly fluid lava are rapidly poured out during an eruption. At its source the lava is generally pahoehoe but changes to aa in its rush down the mountain. At the summit, flows are usually less than 6 feet thick and most often only a few

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[13] Stearns, H. T., The explosive phase of Kilauea Volcano, Hawaii, in 1924: Bull. volcanologique, nos. 5 and 6, pp. 193–209, 1925.

[14] Stearns, H. T., and Clark, W. O., op. cit., p. 52, 1930.

inches thick. On the lower slopes they average 10 feet in thickness but, where pools form, the thickness of individual flows may attain 50 feet or more.

During short-lived eruptions, aa is most abundant as the pahoehoe changes quickly to aa. During long eruptions, the pahoehoe river crusts over and builds one or more feeding tubes which conduct the lava many miles with but slight loss of heat. The flow of 1859 lasted 10 months and is 33 miles long. It produced pillow lava where it ran into the sea.[15] The flows from Mauna Loa that go north and northeast are building up the saddles between Mauna Loa and Mauna Kea and Mauna Loa and Hualalai. These flows are much thicker than usual and have gentle dips where ponded against older mountains, a helpful criterion for determining the relative ages of adjacent volcanoes.

The rocks of Mauna Loa are divided into three units. All are olivine basalts. The oldest is the Ninole volcanic series. It forms the core of the mountain and is exposed in the ancient divide between the part-filled canyons in the southeast slope. One intercalated vitric tuff bed 15 feet thick lies 500 feet below the top of the series. A steep angular erosional unconformity separates the Ninole lavas from the overlying Kahuku volcanic series. The latter attains a thickness of 600 feet and is separated from the overlying Kau volcanic series by a thick mantle of Pahala ash 5 to 50 feet thick. A few of the Kahuku flows interfinger with the ash. The Kau volcanic series are fairly fresh lavas, commonly bare and rocky in dry areas and rarely more than 25 feet thick except in the upper part of Mauna Loa where they exceed 800 feet in thickness. The historic member of the Kau volcanic series comprises the lavas erupted since 1832. Pertinent data regarding their volume and area are given in the accompanying table.

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[15] Alexander, W. D., Mauna Loa's greatest eruption: Mid-Pacific Magazine, vol. 45, p. 318, 1933.

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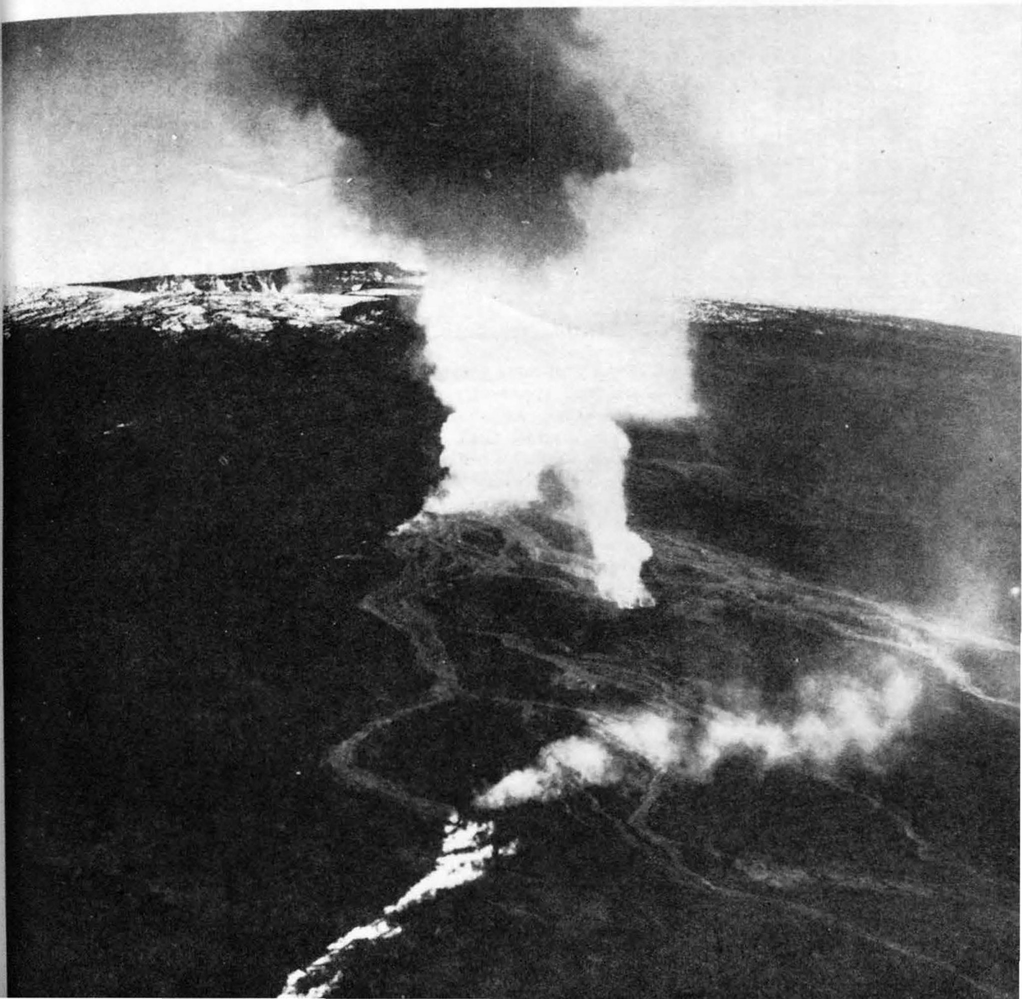
Opposite page, top: Plate 11A. Eruption of Mauna Loa Volcano as seen from Hilo, April 1940. Photo by Hilo Photo Supply.

Bottom: Plate 11B. Flank eruption of 1935 of Mauna Loa Volcano. Photo by U. S. Navy.



Eruptions of Mauna Loa[a]

(Prepared by G. A. Macdonald)

Date of commencement		Approximate duration (days)		Location of principal outflow	Altitude of main vent (feet)	Approximate repose period since last eruption (months)	Area of lava flow (square miles)	Approximate volume of lava (cubic yards)
Year	Month and day	Summit eruption	Flank eruption					
1832	June 20	21	(?)	SW. rift	8,200(?)	.....	6.8(?)	90,000,000(?)
1843	Jan. 9	5	90	N. flank	9,800	126	20.2	250,000,000
1849	May	15	.....	Caldera	[d]13,000	73	....	....
1851	Aug. 8	21	(?)	Caldera & SW. rift	13,300	26	6.9	90,000,000
1852	Feb. 17	1	20	NE. rift	8,400	6	11.0	140,000,000
1855	Aug. 11	.....	450	do.	10,500(?)	41	[b]12.2	150,000,000
1859	Jan. 23	<1	300	N. flank	9,200	26	[c]32.7	[c]600,000,000
1865	Dec. 30	120	.....	Caldera	13,000	73	....	....
1868	Mar. 27	1	[e]15	SW. rift	3,300	23	[c]9.1	[c]190,000,000
1872	Aug. 10	[f]60	.....	do.	13,000	52	....	....
1873	Jan. 6	2(?)	.....	do.	13,300	3	....	....
1873	Apr. 20	547	.....	do.	13,000	3	....	....
1875	Jan. 10	30	.....	do.	13,000	2	....	....
1875	Aug. 11	7	.....	do.	13,000	6	....	....
1876	Feb. 13	Short	.....	do.	13,000	6	....	....
1877	Feb. 14	10	[g]1	W. flank	−180±	12	....	....
1880	May 1	6	.....	Caldera	13,000	38	....	....
1880	Nov. 1	.....	280	NE. rift	10,400	6	24.0	300,000,000
1887	Jan. 16	.....	10	SW. rift	5,700	65	[c]11.3	[c]300,000,000
1892	Nov. 30	3	.....	do.	13,000	68	....	....
1896	Apr. 21	16	.....	do.	13,000	41	....	....
1899	July 4	4	19	NE. rift	10,700	38	16.2	200,000,000
1903	Oct. 6	60	.....	Caldera	13,000	50	....	....
1907	Jan. 9	<1	15	SW. rift	6,200	37	8.1	100,000,000
1914	Nov. 25	48	.....	Caldera	13,000	94	....	....
1916	May 19	.....	14	SW. rift	7,400	16	6.6	80,000,000
1919	Sept. 29	Short	42	do.	7,700	40	[c]9.2	[c]350,000,000
1926	Apr. 10	Short	14	SW. rift	7,600	77	[h]13.4	[c]150,000,000
1933	Dec. 2	17	<1	Caldera & SW. rift	13,000	91	2.0	100,000,000
1935	Nov. 21	<1	42	NE. rift	12,100	23	[i]13.8	160,000,000
1940	Apr. 7	133	<1	Caldera & SW. rift	13,000	51	[j]3.9	100,000,000
1942	Apr. 26	2	13	NE. rift	9,200	20	[k]10.6	100,000,000
Total		1,136	1,314				211.2+	3,450,000,000

[a] The duration for most of the eruptions previous to 1899 is only approximate. Heavy columns of fume at Mokuaweoweo, apparently representing copious gas release accompanied by little or no lava discharge, were observed in January 1870, December 1887, March 1921, November 1943, and August 1944. They are not indicated in the table.

[b] Upper end of the flow cannot be identified with certainty.

[c] Area above sea level. The volume below sea level is unknown, but estimates give the following orders of magnitude: 1859—300,000,000 cubic yards; 1868—100,000,000 cubic yards; 1887—200,000,000 cubic yards; 1919—200,000,000 cubic yards; 1926—1,500,000 cubic yards. These are included in the volumes given in the table.

[d] All eruptions in the caldera are listed at 13,000 feet altitude, although many of them were a little lower.

[e] Flank eruption started April 7.

[f] Activity in the summit caldera may have been essentially continuous from August 1872 to February 1877, only the most violent activity being visible from Hilo.

[g] Submarine eruption off Kealakekua, on the west coast of Hawaii.

[h] 2.5 square miles of this is the area of the thin flow near the summit. An unknown area lies below sea level.

[i] About 0.5 square mile of this is covered by the thin flank flow above the main cone and 0.8 square mile is in Mokuaweoweo Caldera.

[j] 2.8 square miles is in Mokuaweoweo Caldera and 1.1 square miles outside the caldera.

[k] 2.8 square miles of this is covered by the thin flank flow near the summit, and 0.5 square mile is in the caldera.

HUALALAI.—Hualalai Volcano is about 17 miles in diameter and is one of the most symmetrical cones in the Hawaiian Islands. The mountain is studded with cinder cones and near the summit is pockmarked with craters. The volcano is built over a northwest rift, a southeast rift, and a poorly developed northeast rift.

Its rocks have been divided into historic, prehistoric, and Waawaa members of the Hualalai volcanic series. The Hualalai volcanic series comprise all the rocks in the mountain. The Waawaa volcanics comprise Puu Waawaa, a trachyte cone, and the lava flow from it. The rocks of the Hualalai volcanic series are chiefly olivine basalts with an incomplete veneer of picrite basalts carrying augite phenocrysts. Only one basaltic andesite has been found.

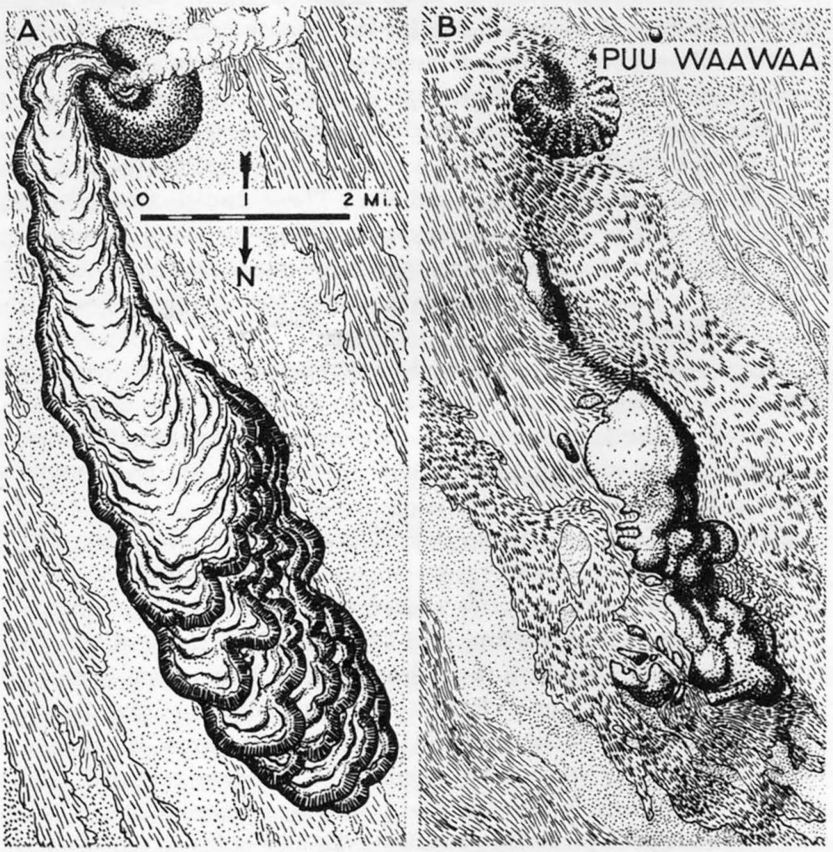


Figure 11. Two stages in the geologic history of Puu Waawaa. A. Massive trachyte lava flow overlying thin basalt flows at close of the eruption. B. Present stage showing cone eroded and lava flow weathered and nearly buried by later basalt flows.

Puu Waawaa, on the north slope, is a cone 1,220 feet high composed of trachyte pumice containing a noticeable amount of obsidian. The writer interprets as a lava flow a ridge of trachyte several hundred feet thick which extends northwest from the cone (fig. 11). This trachyte ridge was first noted by Cross.[16] It is overrun in places by later aa flows from Hualalai, a fact that indicates basalt sometimes follows trachyte in the closing phase of a Hawaiian volcano. The only other soda trachytes are on Kohala Mountain, but Puu Waawaa does not lie on the extension of any Kohala rift; hence, it is likely the result of local differentiation in the Hualalai hearth.

Hualalai was last active in 1800–1801 when voluminous lava flows poured from a long crack on the northwest flank. Known as the Kaupulehu flow, it is remarkable for its cognate inclusions. The lava contains thousands of tons of angular and subangular dunite and gabbro xenoliths mostly less than a foot in diameter. Feldspar crystals, some of gem quality, reaching three-quarters of an inch long are also found. Near the source vent small xenoliths coated with lava of 1801 are piled up like cobbles. These dunite xenoliths look like green candies dipped in chocolate. Before eruption, apparently, the magma stoped away a large precooled mass of dunite and gabbro. Also remarkable are the lava stalactites on the sides of the channels in the flow.

A line of spatter cones below the main belt road in the same area marks the source of a black flow known as the Huehue flow, which, according to the Hawaiians, was also erupted in 1801.[17] The olivine basalt contains pieces of partly charred wood in its tree molds as does the Kaupulehu flow.

KOHALA.—Kohala Volcano was built over a northwest rift, a southeast rift, and a poorly developed southwest rift. Along the northwest and southeast rifts numerous cinder cones are clustered. The mountain is 21 miles long and 13 miles wide. Much of the south slope is buried under lava flows from Mauna Kea. Deep gorges are incised in the east slope. Faults are responsible for the direction of the headwaters of Waipio and Honokane Streams. A sphagnum swamp lies to the east of the summit. A traverse revealed hidden in the swamp and in the adjacent jungle, numerous small, deep, narrow, collapsed pits along fault cracks and holes in aa flows.

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[16] Cross, Whitman, An occurrence of trachyte on the island of Hawaii: Jour. Geology, vol. 12, pp. 510–523, 1904.

[17] In a personal communication dated Jan. 14, 1938, Dr. T. A. Jaggar states that "Miss Paris says natives told her father the Kaupulehu flow was the first (1800) and higher, and the Huehue flow was the second (1801) and lower flow."

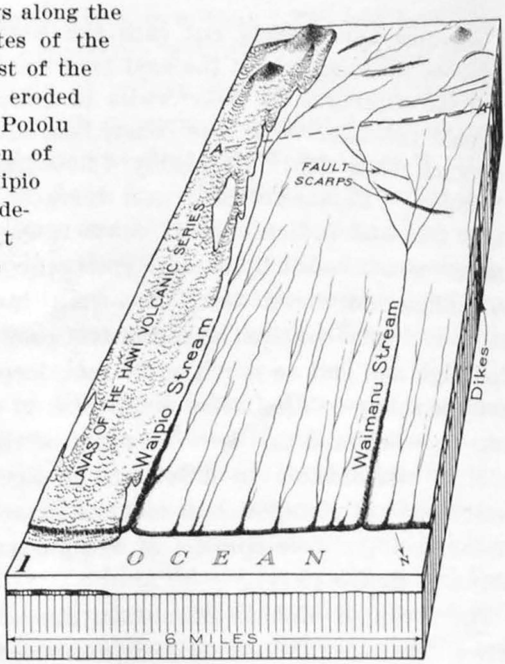
Streams have barely cut into the west slope of the mountain; whereas the canyons on the east side are more than 2,000 feet deep and the sheerness of their walls is unsurpassed anywhere in the islands (pl. 12). Near the coast, bedrock floors of the gorges are drowned to a depth of nearly 1,000 feet, as noted long ago by Branner.[18] Remnants of gravel terraces rise in these canyons to 1,100 feet and indicate great submergence following the deep submergence succeeded by a later emergence. The west or lee coast is not cliffed and, except near the several large cones, has only a thin soil covering in contrast with the east coast where sea cliffs are 1,200 feet high and soil as much as 20 feet deep. This great difference is not due solely to dissimilar conditions of rainfall and roughness of seas on windward and leeward sides of the volcano, but at least in part is attributable to difference in age. The lava beds on the west slope are younger than most of those on the east. Four stages in the geologic development of Waipio and Waimanu Valleys are shown in figure 12.

The rocks of Kohala Mountain are divided into two volcanic series. The older Pololu series is composed of thin-bedded primitive olivine, basalts with porphyries at the top in most places. The younger Hawi series is composed chiefly of oligoclase andesites and a few soda trachytes. Some of the more viscous flows formed bulbous domes but bulky cinder cones lie on the fissure vents of most of the flows. The Hawi lavas lie mostly at the top of the mountain and are usually from 1 to 3 flows thick. A thin red lateritic soil from a few inches to several feet thick separates the Hawi from the underlying Pololu lavas except in the wet windward slope where the lavas are separated by an erosional unconformity. A Hawi flow several hundred feet thick spilled into Pololu Valley. The later Hawi lavas interfinger south of Waipio Valley with the lavas of the Hamakua series from Mauna Kea. A late flow in the Hamakua series spilled into the southeast side of Waipio Valley.

A graben half a mile wide and 3 miles long crosses the summit of Kohala Mountain. It is bordered by faults arranged en echelon. The faults cut both volcanic series. They appear to outline a caldera 2 miles wide and 3 miles long that was largely filled by the Hawi volcanic series. The Hawi lavas did not overtop the walls of the graben; hence, most of the late lavas flowed northwestward and southeastward before fanning over the slopes. This fault-controlled distribution left two large areas of Pololu lavas uncovered, one to the southwest and the other to the northeast of the summit graben.

[18] Branner, J. C., Notes on the geology of the Hawaiian Islands: Am. Jour. Sci., 4th ser., vol 16, no. 94, p. 301, 1903.

Stage 1. Waipio Stream flows along the margin of the heavy andesites of the Hawi volcanic series. The rest of the block consists of older easily eroded thin-bedded basalts of the Pololu volcanic series. The location of the upper tributaries of Waipio and Waimanu streams are determined partly by fault scarps. The line AA′ is the north boundary of a dike swarm.



Stage 2. Waipio and Waimanu streams have cut deep canyons in the carapace of the mountain. Hiilawe, Waimanu, and Waihilau streams tap water confined between a few stray dikes whereas the headwaters of Waipio Stream have tapped water confined in the main dike swarm which trends parallel to the line AA′. The sea has cut high cliffs along the shore. The spur on the left side of Waipio Canyon being armored by thick andesites has resisted wave erosion better than the rest of the block consisting of basalt.

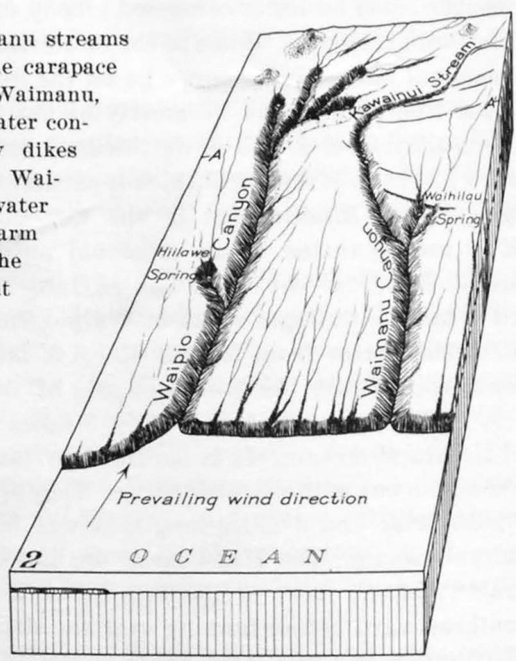
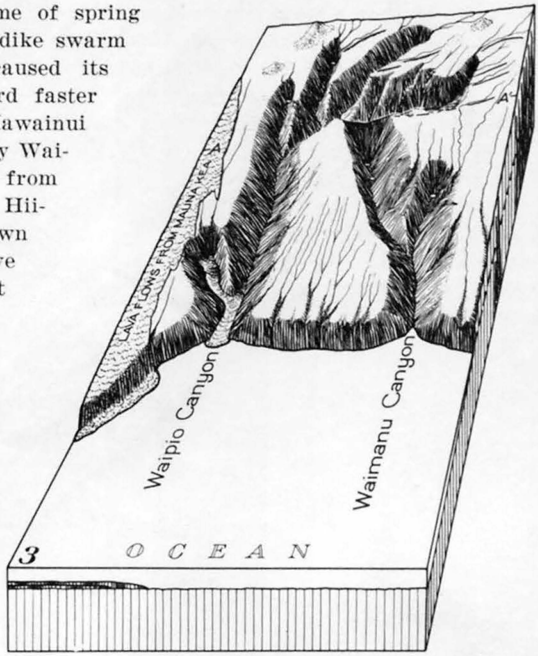
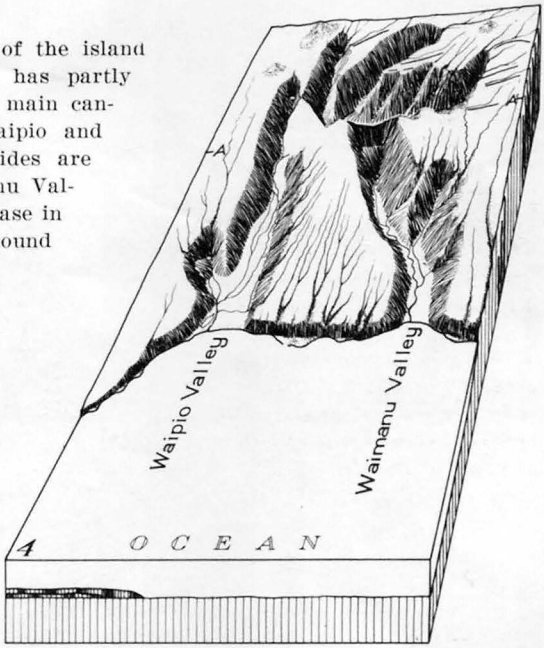


Figure 12. Four stages showing the development

Stage 3. The large volume of spring water tapped in the main dike swarm by Waipio stream has caused its tributaries to cut headward faster so that the ancestral Kawainui stream has been captured by Waipio Stream. A lava flow from Mauna Kea has spilled into Hiilawe cove and flowed down Waipio Valley. Others have spilled over the sea cliff left of Waipio Canyon slowing down marine erosion in this sector. High cliffs have been cut by the sea on the weak basalts.



Stage 4. A submergence of the island by more than 1,200 feet has partly drowned the sea cliff and main canyons. Alluvium floors Waipio and Waimanu valleys. Landslides are filling the head of Waimanu Valley as a result of the decrease in flow from loss of more ground water to Waipio Stream.



f Waipio and Waimanu valleys, Hawaii.

Opposite page: Plate 12. Looking into Waipio Valley showing the flat alluvial floor and the spring coves at its head. The cove on the left is Hiilawe into which spilled a lava flow from Mauna Kea. In the background are andesite cinder cones of the Hawi volcanic series. Photo by U.S.A.A.F.

←

Two hundred and fifty dikes are exposed in the canyons in the windward slope. They range from a few inches to 40 feet in width and average about 2 feet. The widest basalt dike is 15 feet. Three hornblende biotite soda trachyte dikes 18, 30, and 40 feet wide respectively, are exposed also. An olivine basalt intrusive a mile long, possibly a stock, is exposed in the Kawainui Branch of Waipio Valley. A few feet of Pahala ash overlies the Hawi volcanic series on the southern slope. Vitric ash beds are common near the summit in this series but scarce in the perifery of the mountain and in the Pololu series. No lithic explosion breccias were found.

KILAUEA.—Kilauea Volcano nestles on the southeast slope of Mauna Loa and merges so imperceptibly with its giant neighbor that significant dimensions cannot be assigned. Lava flows from Mauna Loa pass over the slopes of Kilauea, and it is entirely possible that some day a flow from Mauna Loa may enter the caldera of Kilauea.

The notable features of Kilauea are: The summit caldera 2.93 miles long and 1.95 miles wide, the active pit crater of Halemaumau which for years at a time contains a lava lake (pl. 9), the high echelon fault escarpments on the south coast, the chain of pit craters on the southeast rift zone, and the long cracks in the southwest rift zone.

A dense forest covers the windward slope of Kilauea, but the Kau Desert on the lee side is nearly devoid of vegetation. There, drifting sand dunes 10 to 20 feet high are formed largely of reworked ash.

It is believed that Kilauea lies on the main volcanic rift passing through Kohala and Mauna Kea and originated when the great faults on the south side of Mauna Loa tapped the magma in this rift.[19] The basement of Kilauea is probably composed of lava from Mauna Loa. Figure 13 is a diagram showing a hypothetical relation of these volcanoes to the interior of the earth.

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[19] Stearns, H. T., and Clark, W. O., Geology and water resources of the Kau District, Hawaii: U. S. Geol. Survey Water-Supply Paper 616, p. 107, 1930.

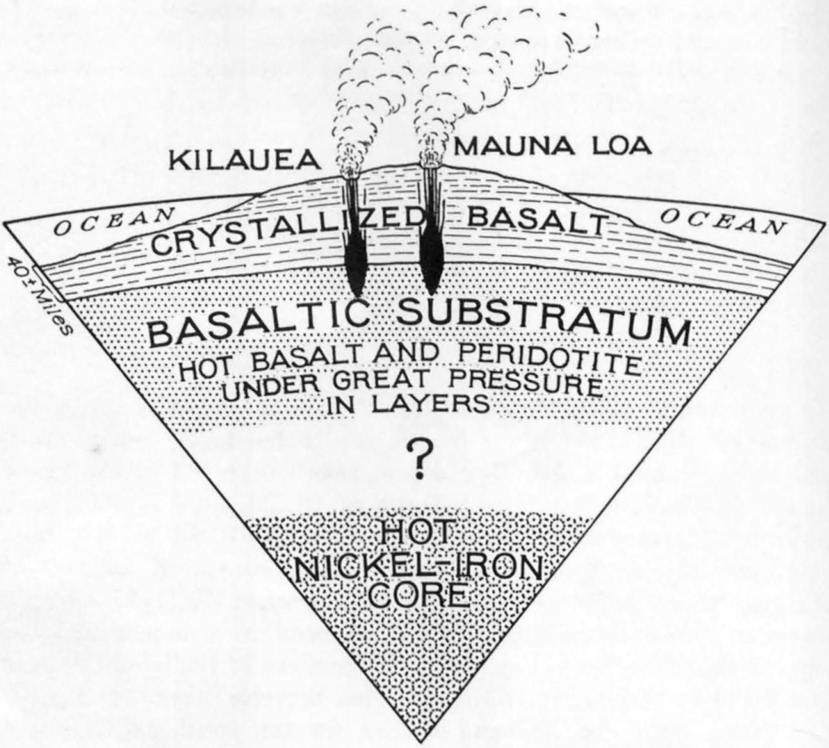


Figure 13. Hypothetical relation of Kilauea and Mauna Loa volcanoes with the interior of the earth.

Kilauea is an ash producer. At least 11 different ash eruptions can be recognized in its surficial deposits,[20] and not all came from Halemaumau. A paroxysmal magmatic explosion took place at Halemaumau in 1790 when part of the army of a warring Hawaiian chieftain was burned to death.

The explosions in 1924 were definitely phreatic and have been attributed to basal ground water. Subsequent studies on the presence of water in the dike complexes or eroded rift zones of the islands of Hawaii show that large quantities of ground water are stored between dikes, hundreds and even thousands of feet above sea level. A plausible explanation for the steam explosions of 1924 is that the water was released from storage in the adjacent dike complex which underlies the southeast rift, as a result of the intense cracking preceding the explosions. If this is true, the foci of the explosions were

[20] Idem, pp. 143–152.

shallow and not below sea level, a position which is mandatory if the basal zone of saturation supplied the water.[21]

Lava flows from Kilauea, except those that pool in depressions, range from a few inches[22] to 15 feet in thickness and average 8 feet. They vary in length from a few feet to several miles. Some lavas chilled so quickly when they came in contact with vegetation that molds of even delicate fern fronds and grass were formed. In the tube of the flow of 1920, lava stalactites 3 feet long and no thicker than a lead pencil are the result of secondary melting. Within historic time, some small flows have issued so quietly that they were not discovered until the lava had cooled, even though the staff of the Hawaiian Volcano Observatory is constantly watching for them. Pertinent data regarding the volume and area of historic flows of Kilauea are given in the accompanying table.

[21] This hypothesis was described by the writer in an article entitled "High-level ground water as a cause of volcanic explosions at Mauna Loa and Kilauea volcanoes, Hawaii," submitted to Dr. T. A. Jaggar of the Hawaiian Volcano Observatory in May 1934 but not published. Dr. Jaggar does not agree with this explanation. Mr. Finch, the present director of the Observatory, believes this hypothesis does explain the explosion of 1924 at Kilauea. See "Lava surgings in Halemaumau and the explosive eruptions in 1924": Volcano Letter no. 479, pp. 1–3, 1943.

[22] Stearns, H. T., The Keaiwa or 1823 lava flow from Kilauea Volcano, Hawaii: Jour. Geology, vol. 34, pp. 336–351, 1926.

Data regarding historic eruptions of Kilauea[a]

(Prepared by G. A. Macdonald)

Year	Date of outbreak	Duration (days)	Altitude (feet)	Location	Approximate repose period since last eruption (months)[b]	Area (square miles)	Volume (cubic yards)
1750(?)	....	....	1,700	E. rift	.....	1.57	19,500,000
1790(?)	....	....	1,100–750	E. rift	.....	3.04	37,670,000
1790[c]	Nov.(?)	....	....	Caldera	.....	No lava	No lava flow
1823	Feb.-July	Short	1,700–250	SW. rift	.....	[d]3.86	[d]15,000,000
1832	Jan. 14	Short	3,650	E. rim of caldera	.....	(?)	(?)
1840	May 30	26	3,100–750	E. rift	.....	[d]6.60	[d]281,000,000
1868	April 2	Short	3,350	Kilauea Iki	.....	.07	(?)
1868	Apr. 2(?)	Short	2,550	SW. rift	.....	.04	250,000
1877	May 4	1(?)	3,500(?)	Caldera wall	.....	(?)	(?)
1877	May 21(?)	....	3,450(?)	Keanakakoi	.....	.04	(?)
1884	Jan. 22[e]	1	−60(?)	E. rift	.....	(?)	(?)
1885	March	80(?)	3,640(?)	Caldera	14	(?)	(?)
1894	Mar. 21	6+	3,690	Caldera	108	(?)	(?)
1894	July 7	4(?)	3,690	Caldera	3.5	(?)	(?)
1918	Feb. 23	14	3,700	Caldera	283	.04	250,000
1919	Feb. 7	[f]294	3,700	Caldera	11	1.60	34,500,000(?)
1919	Dec. 21	221	3,000	SW. rift	<1	5.00	62,000,000
1921	Mar. 18	7	3,700	Caldera	7.5	.77	8,800,000
1922	May 28	2	2,650–2,400	Makaopuhi & Napau	14	.04	(?)
1923	Aug. 25(?)	1	3,000	E. rift	15	.20	100,000
1924[g]	May 10	17	....	Caldera	8	No lava	No lava
1924	July 19	11	2,365	Halemaumau	2.5	.02	320,000
1927	July 7	13	2,400	Halemaumau	35	.04	[g]3,160,000
1929	Feb. 20	2	2,500	Halemaumau	19	.06	1,920,000
1929	July 25	4	2,560	Halemaumau	5	.08	[h]3,600,000
1930	Nov. 19	19	2,600	Halemaumau	15.5	.09	[i]8,480,000
1931	Dec. 23	14	2,700	Halemaumau	12.5	.12	[j]9,640,000
1934	Sept. 6	33	2,800	Halemaumau	44	.16	9,500,000

[a] Many eruptions have occurred on the floor of the caldera, but only a few of the later ones are listed here, data being inadequate or totally lacking for the earlier ones. On January 11, 1928, a small amount of lava was extruded on the floor of Halemaumau, but this is believed to have been squeezed out by the weight of a heavy landslide on the crust of the 1927 lava which was still fluid beneath (Jaggar, Volcano Letter 370, 1932).

[b] During the early historic period Kilauea Caldera was observed only occasionally, and no definite record exists of the many caldera flows which are known to have occurred.

[c] Violently explosive.

[d] Area above sea level. The volume below sea level is unknown; but estimates give the following orders of magnitude: 1832—3,000,000 cubic yards; 1840—200,000,000 cubic yards. These are included in the volumes given in the table.

[e] Pacific Commercial Advertiser, Feb. 2, 1884. "A column of water, like a dome, shot several hundred feet up into the air, accompanied with clouds of smoke and steam." No further eruption was observed next day.

[f] Several separate flows, with short intervals without extrusion.

[g] Violent phreatic explosions, possibly accompanied by a submarine lava flow on the E. rift.

[h] Powers, H. A., Volcano Letter 243, 1929.

[i] Jaggar, Volcano Letter 311, 1930.

[j] Jaggar, Volcano Letter 366, 1931.

The eruptive cycle of Kilauea apparently begins with an explosion which forms a large pit on the floor of the caldera. Concurrent and subsequent collapse widens this pit until most of the floor of the caldera is engulfed, as happened after the explosions in 1790, or only a small part of it, as after the explosions of 1924. Then for several decades eruptions, separated by quiescent intervals of several months or several years, break out in the floor or wall of the pit and slowly fill it up. These eruptions produce cinder and spatter cones and lava lakes which solidify soon after the fountain activity ceases. Small quantities of pumice from the fountains are blown away and accumulate to the leeward on the floor and on the rim of the caldera. Slowly but steadily the pit fills. Finally the lava erupts in the pit without fountaining and the slowly rising gases keep the lava lake hot and in motion for months and even years. Eventually the pit fills, and lava flows over the caldera floor. In 1921 a small tongue of lava overflowed the south rim of the caldera. The lava lake may abruptly sink out of sight leaving a fuming, dark, collapsing pit. If a lake so disappears, the lava is diverted into flank flows, submarine eruptions, or intrusions into the mountain; or it may return to the reservoir whence it came.

During the lake phase, islands of solid aa form, and these rise and fall in the molten lake. Jaggar and his associates have contributed invaluable studies of the lava lake. They established its shallow depth by soundings, found tidal motions in the lake, proved the temperature was hotter at the surface than at the bottom, observed flames caused by burning gases, and collected and analyzed the gases from source wells and from cracks. In addition, they kept a detailed record of the cracks and the earthquakes, the areas and volumes of the flows, the tilting and tumescence of the mountain, and a vast amount of other data applying to Kilauea and Mauna Loa (see Bibliography).

The volcanic rocks of Kilauea have been divided into two units, the Hilina and Puna volcanic series. The Hilina volcanic series is more than 1,000 feet thick and consists of basalts and several thin vitric tuff beds. It crops out only in the high fault escarpments in the southern slope of Kilauea. It is overlain and separated from the Puna volcanic series by 10 to 40 feet of Pahala ash. The lavas of the Puna series thicken toward the summit and reach a thickness of 490 feet in the wall of the caldera. A few inches to 30 feet of ash caps the series in the vicinity of the caldera. The Puna volcanic series is divided into the prehistoric and historic members.

The faults on the southern coast are arranged en echelon and dip from 30° to 45° seaward. The aggregate displacement is 1,500 feet in places. The whole slope for four miles inland is actively foundering. Many of the late flows in the Puna series have been displaced since they spilled over the scarps (fig. 14).

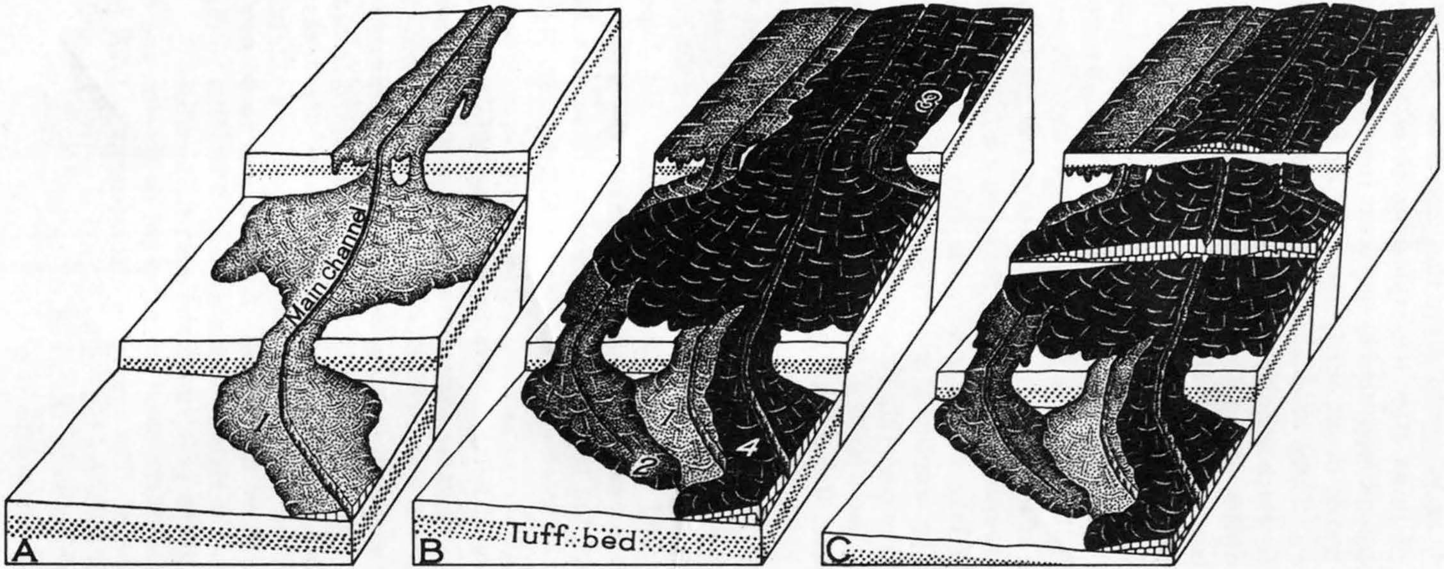


Figure 14. Diagram illustrating the relation of faulting to successive lava flows. **A.** Lava flow spills over two fault scarps forming narrow cascades on the scarps and fans at their bases. The front block is tilted down to the right which deflects the lava in that direction. **B.** Four lava flows have cascaded over the scarps. The inner scarp has been nearly buried. **C.** A new fault has split the middle block in two, the innermost fault has moved while the outermost fault has remained stationary. The two epochs of faulting are distinguished by the hanging plasters and cascades of lava on the innermost scarp and their absence on the newly formed scarp.

Maui, like Oahu, is composed of two volcanic cones. East Maui, or Haleakala Volcano, famed for its gigantic summit depression of unusual shape, is 10,025 feet high and 33 miles across (pl. 13). West Maui, 5,788 feet high and 18 miles across, is distinguished for the Needle, a rock pinnacle in the spectacular Iao Valley (pl. 14). The stratigraphic rock units on the island are given in the accompanying table and their distribution is shown in figure 15. Eight stages in the geologic history of Maui are shown in plates 15 to 18.

Stratigraphic rock units on the island of Maui

Major geologic unit	Major rock units	
	East Maui	West Maui
Historic volcanic rocks	Volcanics erupted in 1750 (?) near Makena	
Recent sediments	Unconsolidated deposits	Unconsolidated deposits
Pleistocene sediments	Calcareous dunes Consolidated earthy deposits Kaupo mudflow	Calcareous dunes Consolidated earthy de-deposits
Pleistocene and Recent volcanic rocks	Hana volcanic series (includes Kipahulu member in Kipahulu Valley)	Lahaina volcanic series
Great erosional unconformity		
Pliocene and Pleistocene (?) volcanic rocks	Kula volcanic series	Honolua volcanic series
	Honomanu volcanic series	Wailuku volcanic series

West Maui.—West Maui is incised by deep amphitheater-headed valleys (pl. 19) and on the east is overlapped by lava flows from Haleakala which have built a saddle known as the Isthmus. Iao Valley is an old caldera tapped by the Wailuku River and enlarged by erosion. Vent breccia at the head of the adjacent Waikapu Canyon indicates that this stream also tapped the caldera or an adjoining crater. Although rift zones are known (pl. 1), this volcano approaches the "central type," in contrast to the "fissure type," because dikes radiate in all directions from the ancient caldera and almost all the lava beds are steep and many were poured from the central vent. Single basaltic dikes as much as 24 feet across, the widest basaltic dikes yet found in the islands, crop out on West Maui. Typically, the basalt is thin-bedded aa and pahoehoe erupted chiefly through narrow cracks so that only a few cinder cones were produced. Toward the close of the basaltic eruptions, violent explosions are indicated by interstratified beds of lithic tuff and agglomerate containing large blocks.

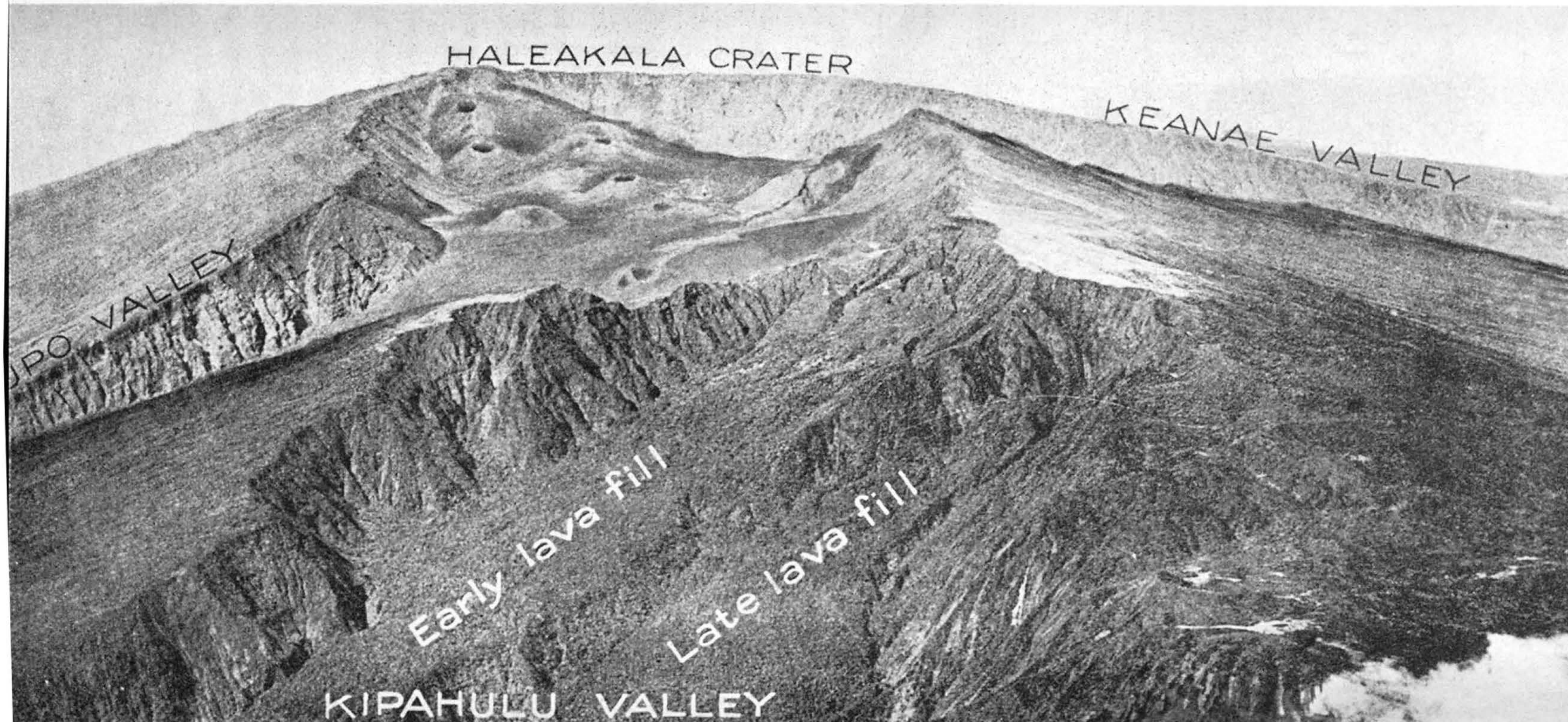


Plate 13. View looking westward across Kipahulu Valley showing the terrace of early Hana lavas (Kipahulu member) Bordered by valley fill of later Hana lavas. The summit depression of Haleakala is in the background. Photo by U.S.A.A.F.

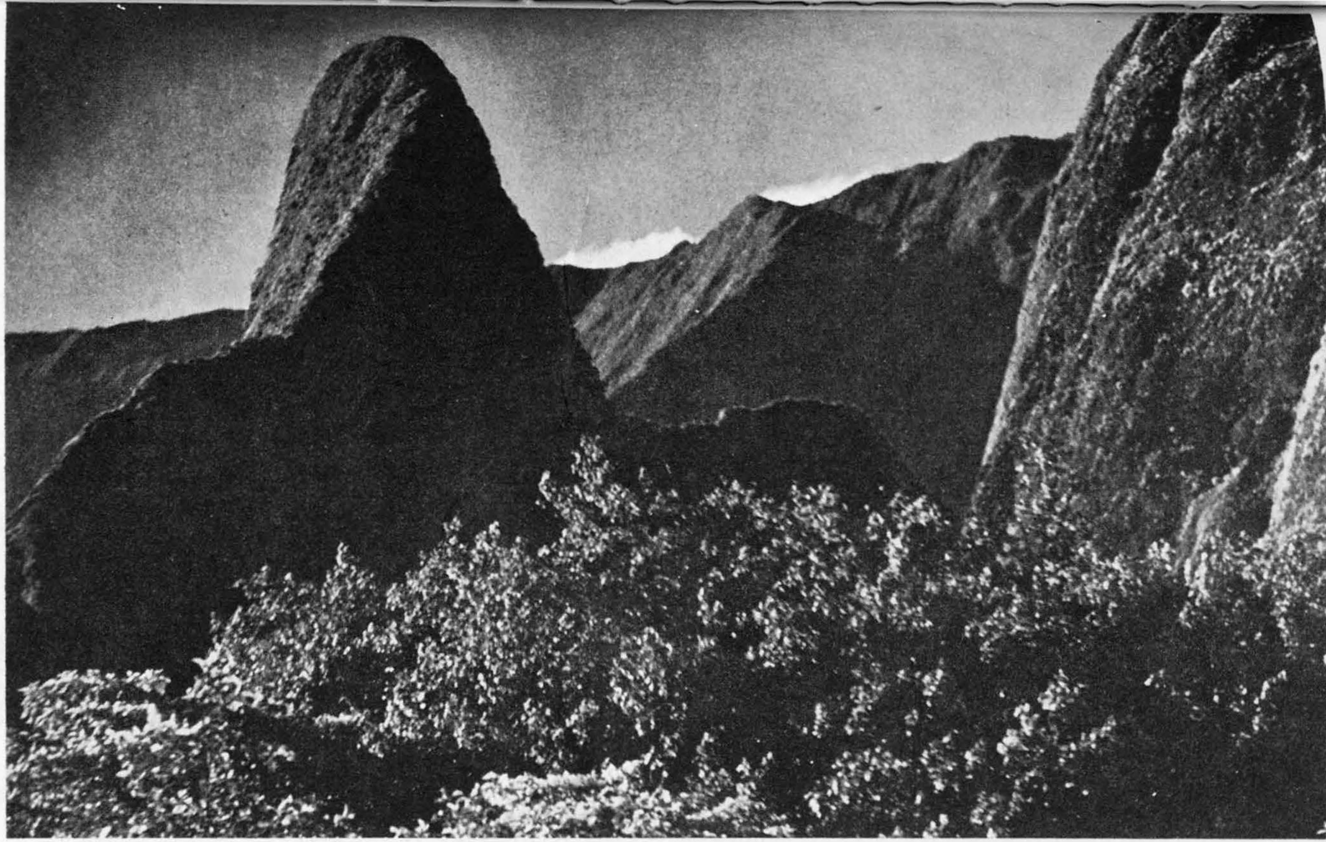
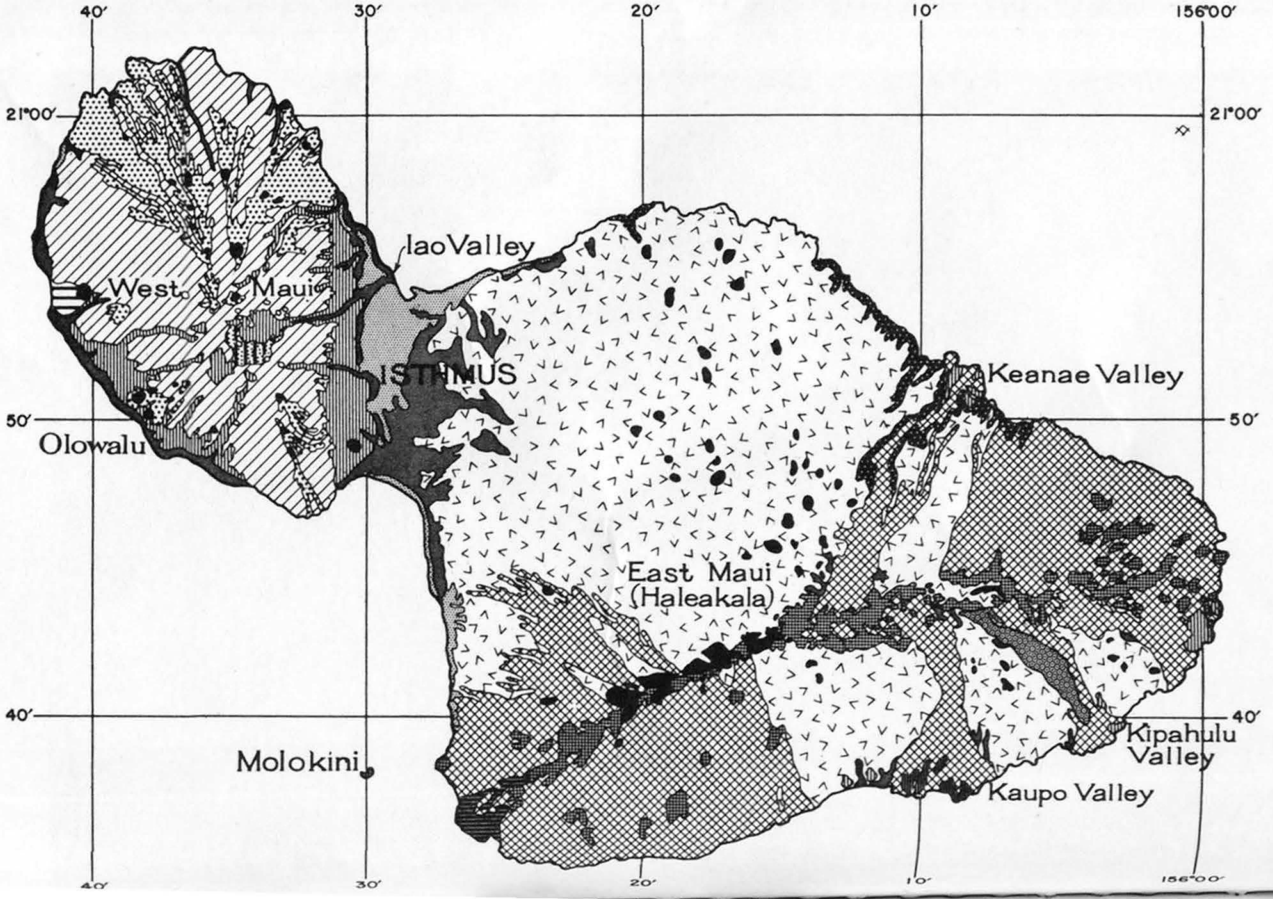


Plate 14. Iao Valley, the ancient eroded caldera of the West Maui Volcano, now cool and clothed with forest verdure and famous for its pinnacle, called the Needle. Photo by Pan Pacific Press Bureau.


40′
30′
20′
10′
156°00′
21°00′
21°00′
50′
50′
40′
40′
Iao Valley
West Maui
ISTHMUS
Keanae Valley
Olowalu
East Maui
(Haleakala)
Kipahulu Valley
Molokini
Kaupo Valley
40′
30′
20′
10′
156°00′

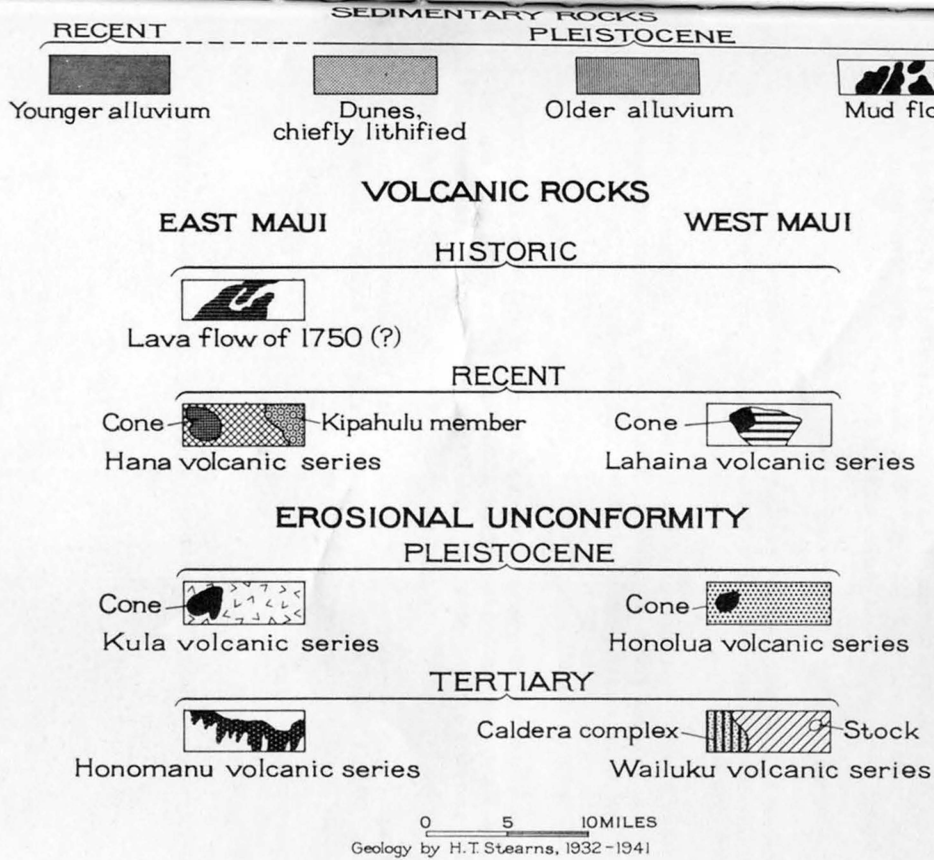


Figure 15. Geologic map of the island of Maui. Faults and dikes omitted.

PLATES 15 TO 18 SHOWING EIGHT STAGES IN THE DEVELOPMENT OF MAUI

15A. Stage 1 in the development of Maui showing the East Maui and West Maui volcanoes as separate islands erupting primitive basalts.

15B. Silhouette of stage 1.

15C. Stage 2 in the development of Maui showing East Maui volcano with a caldera on its summit and faults on its south side, and West Maui volcano erupting Honolua lavas and joined to Lanai and Molokai volcanoes.

16A. Stage 3 in the development of Maui showing East and West Maui joined with Kahoolawe, Lanai, and Molokai. East Maui volcano is erupting Kula lavas. Present outline of Maui indicated by a dotted line.

16B. Silhouette of stage 3.

16C. Stage 4 in the development of Maui showing the canyon-cutting period of early Pleistocene time with all volcanoes dormant. Present outline of Maui indicated by a dotted line.

17A. Stage 5 in the development of Maui after the great submergence during the Olowalu 250-foot stand of the sea. East and West Maui are separate islands. The valleys have been deeply filled with alluvium.

17B. Silhouette of stage 5.

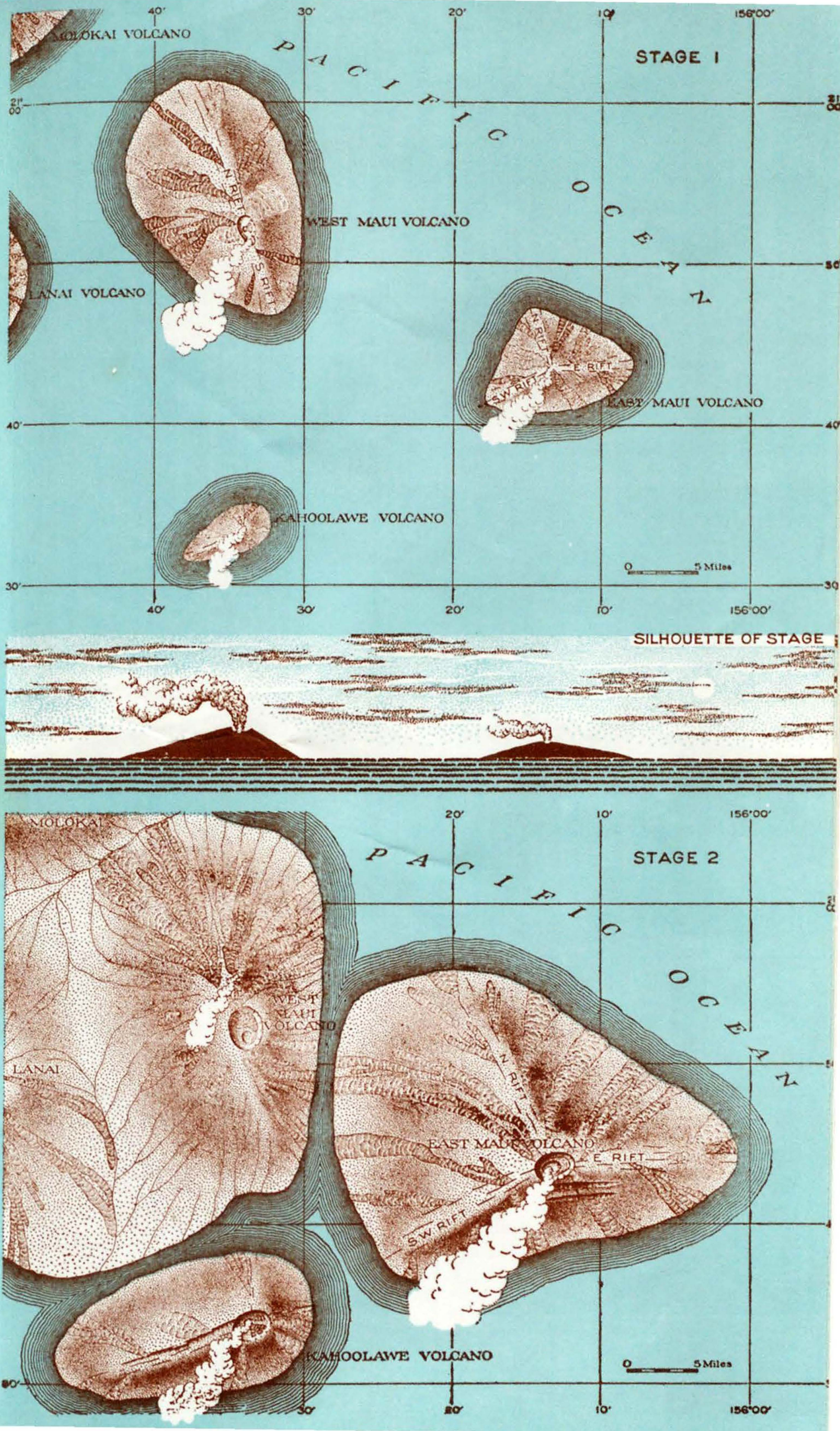
17C. Stage 6 in the development of Maui showing East and West Maui united during the Kahipa minus 300-foot stand of the sea. Hana lavas have started to fill the canyons on East Maui, and the Kaupo mud flow has just been emplaced.

18A. Stage 7 in the development of Maui showing the island during the Waipio minus 60-foot stand of the sea with the Hana and Lahaina lavas being erupted and dunes forming on the Isthmus.

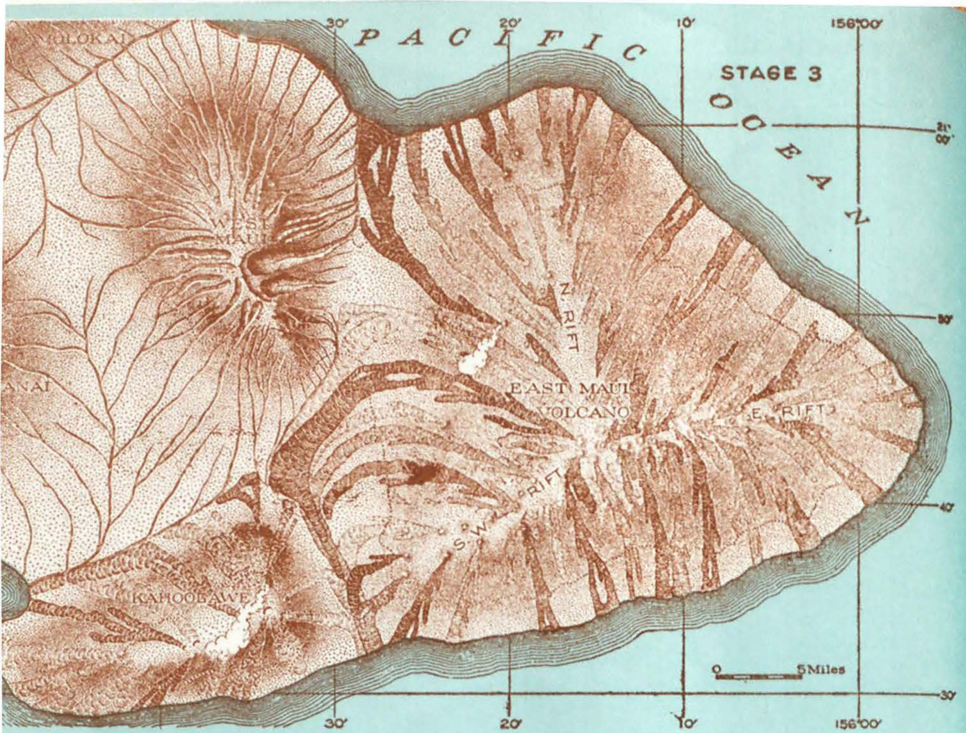
18B. Silhouette of stage 7.

18C. Stage 8, Maui at the present time.

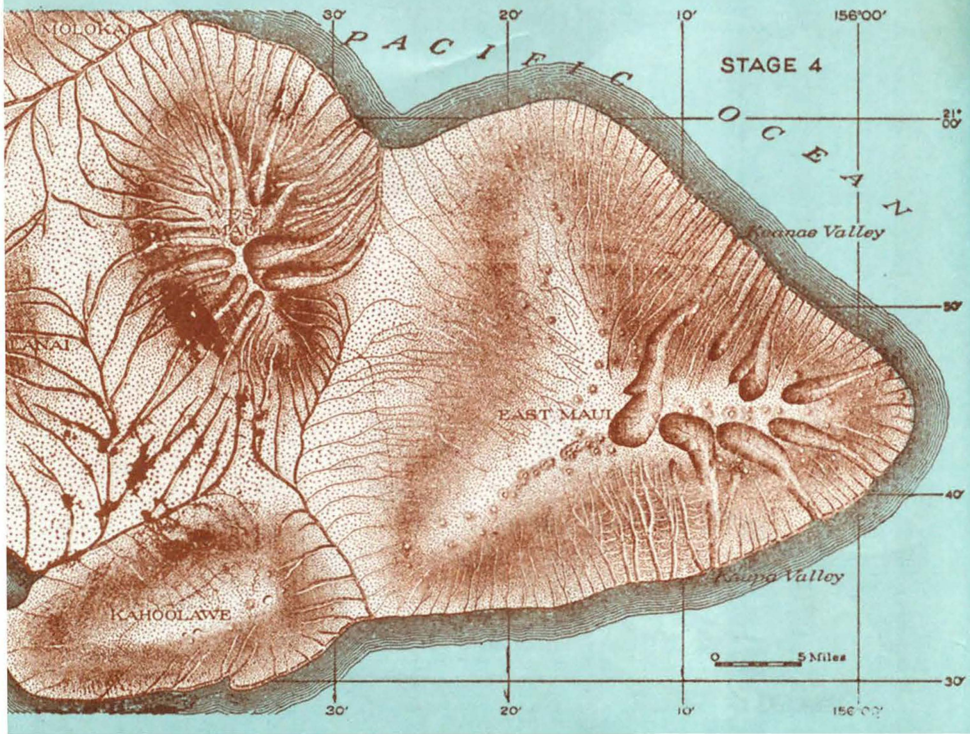
(Silhouettes are sections of Maui where important changes have occurred.)

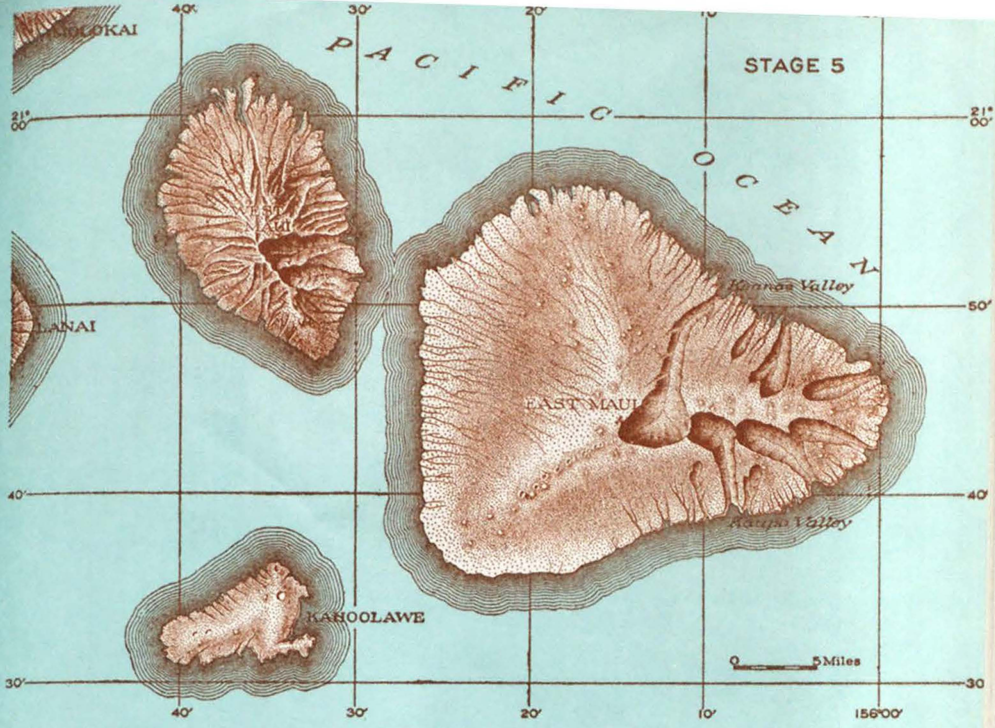


STAGE 1
MOLOKAI VOLCANO
PACIFIC OCEAN
N RIFT
WEST MAUI VOLCANO
S RIFT
LANAI VOLCANO
N RIFT
E RIFT
SW RIFT
EAST MAUI VOLCANO
KAHOOLAWE VOLCANO
0 5 Miles
40′
30′
20′
10′
156°00′
21° 00′
40′
30′
SILHOUETTE OF STAGE
STAGE 2
MOLOKAI
PACIFIC OCEAN
WEST MAUI VOLCANO
LANAI
N RIFT
EAST MAUI VOLCANO
E RIFT
SW RIFT
KAHOOLAWE VOLCANO
0 5 Miles
20′
10′
156°00′
30′

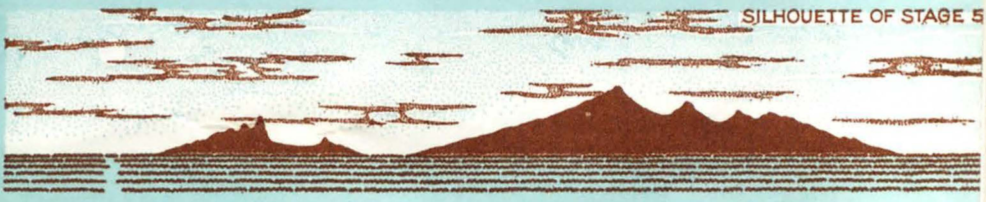

STAGE 3
PACIFIC OCEAN
MOLOKAI
LANAI
KAHOOLAWE
N. RIFT
EAST MAUI VOLCANO
E. RIFT
S.W. RIFT
5 Miles
30′
20′
10′
156°00′
21° 00′
50′
40′
30′


SILHOUETTE OF STAGE 3

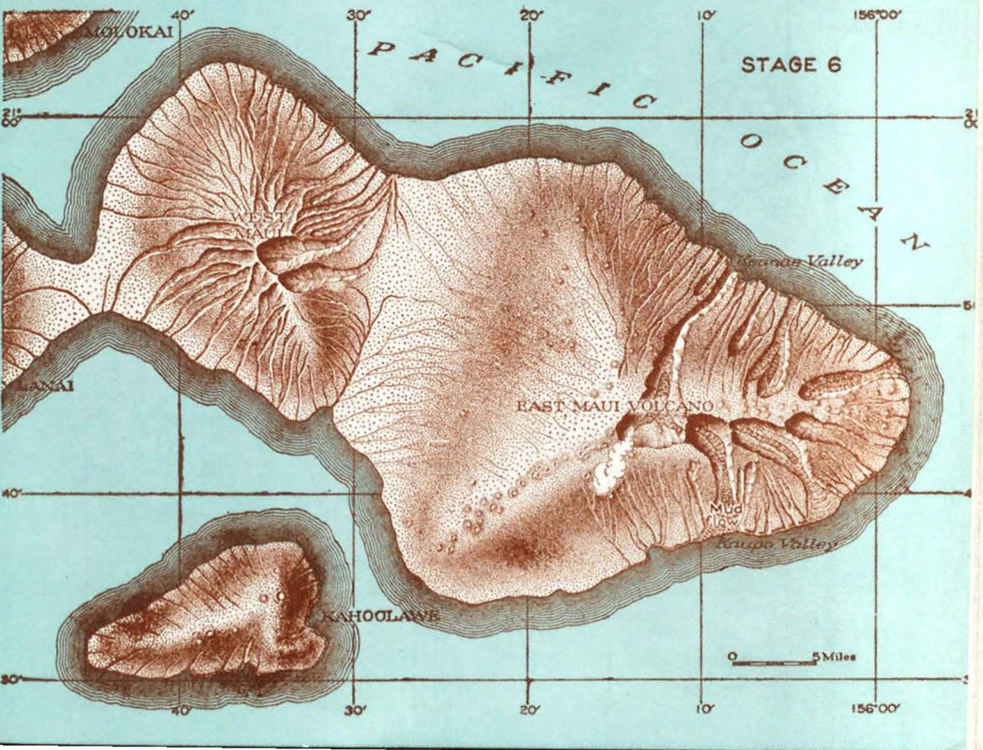

STAGE 4
PACIFIC OCEAN
MOLOKAI
LANAI
KAHOOLAWE
WEST MAUI
EAST MAUI
Keanae Valley
Kaupo Valley
5 Miles
30′
20′
10′
156°00′
21° 00′
50′
40′
30′



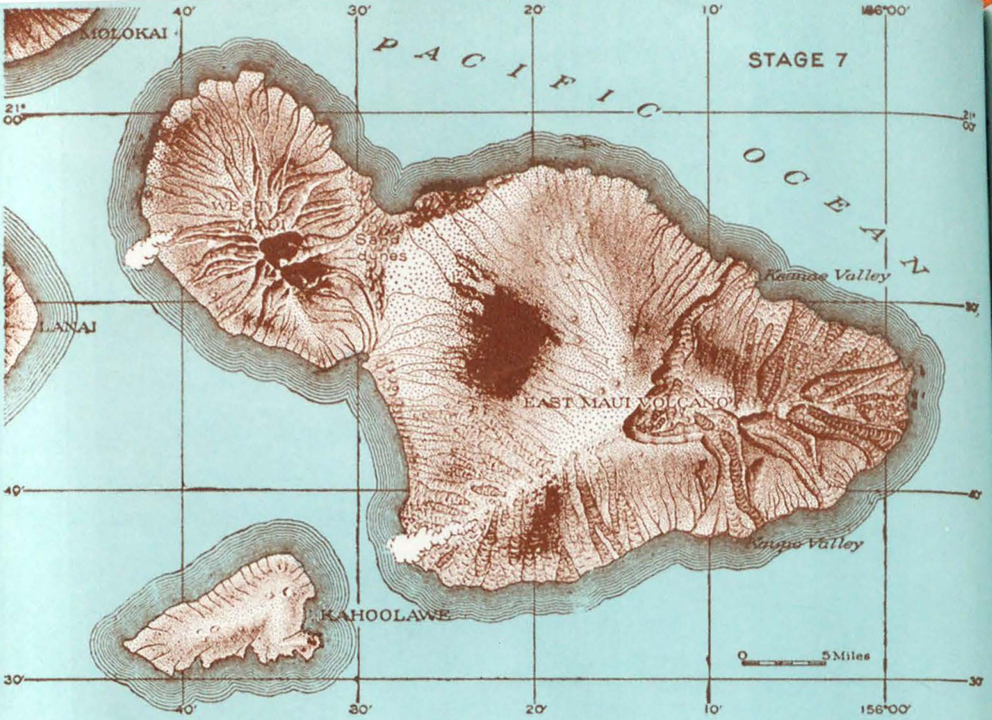
STAGE 5
PACIFIC
OCEAN
LANAI
EAST MAUI
Kaupo Valley
KAHOOLAWE
0 5 Miles
21° 00′
50′
40′
30′
156°00′



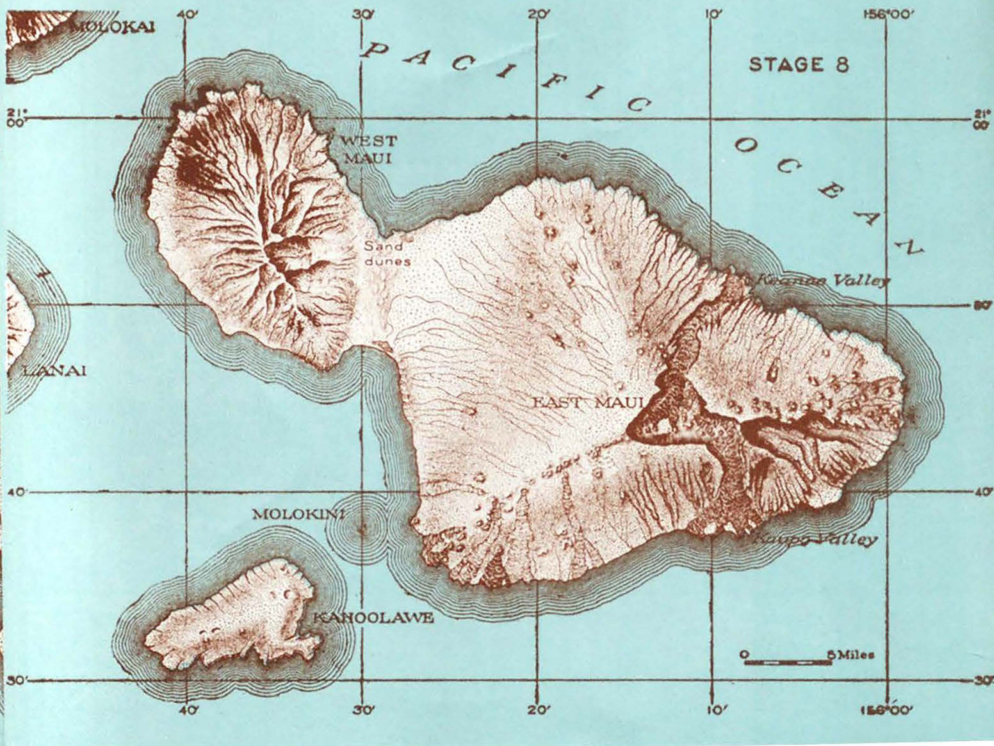
SILHOUETTE OF STAGE 5



MOLOKAI
STAGE 6
PACIFIC
OCEAN
WEST MAUI
LANAI
EAST MAUI VOLCANO
Keanae Valley
Mud flow
Kaupo Valley
KAHOOLAWE
0 5 Miles
21° 00′
40′
30′
20′
10′
156°00′


STAGE 7
PACIFIC OCEAN
MOLOKAI
LANAI
Sand dunes
Keanae Valley
EAST MAUI VOLCANO
Kaupo Valley
KAHOOLAWE
0 5 Miles


SILHOUETTE OF STAGE 7


STAGE 8
PACIFIC OCEAN
WEST MAUI
Sand dunes
Keanae Valley
LANAI
EAST MAUI
MOLOKINI
Kaupo Valley
KAHOOLAWE
0 5 Miles

Extrusion of the basalts, which constitute the mass of the mountain was followed by a rest period during which a few inches to several feet of soil formed. These basaltic volcanics form the Wailuku volcanic series. Then, oligoclase andesites and stiff trachyte from fissures and local vents almost completely veneered the dome. These rocks form the Honolua volcanic series. The light color produced by the weathering of the andesite and trachyte in contrast with the darker product from the decomposition of basalt gives the mountain the appearance of a brown cake partly covered with white frosting. Trachyte cones are prominent, and many of them are bulbous domes (fig. 6). The presence of soils 20 feet or more thick indicates that the volcano probably became extinct in Pliocene or earliest Pleistocene time.

During the erosion cycle when the great canyons were carved, extensive fanglomerates were laid down along the east side of the mountain and smaller ones along part of the leeward coast (pl. 20). Some of these deposits are probably marine; for in the later Pleistocene time, the island passed through a series of submergences and emergences similar to those of Oahu, as shown by the presence of fossiliferous conglomerates up to an altitude of 250 feet near Olowalu, and by the loss of lateritic soil through marine erosion at points now 1,200 feet above sea level. Near the southern coast, a few flows and cones of picrite basalt and nepheline basanite were erupted in late Pleistocene time and rest upon, and in places are inter-stratified with, the fanglomerates. These rocks form the Lahaina volcanic series.

East Maui or Haleakala.—The summit depression of East Maui or Haleakala Volcano is 7 miles long and 2½ miles wide, and its floor is covered with bare flows and large cinder cones (pl. 13). The flanks of the mountain are covered with flows some of which are black and bare. According to Hawaiian tradition, one flow was erupted as recently as 1750. The volcano was built over three rift zones (pl. 1) and is unlike West Maui because these rifts are studded with large cinder cones. Most of the lava flows, except those on the Isthmus, dip about 12°. In many places three series of lavas can be distinguished. The lower unit, the Honomanu volcanic series, consists of thin-bedded, typical basaltic pahoehoe and aa. Overlying this unit conformably is the Kula volcanic series, composed chiefly of thicker andesitic aa flows which issued in a more viscous state and which contain many interstratified, thin ash-soil layers. Because many of the large cinder cones were built during this epoch, ash beds are more numerous than in the lower underlying Honomanu basalts. Some olivine basalts and picrite basalts occur in the Kula series.


2
3
1

Opposite page: Plate 19. Head of Honokohau Canyon, 2,300 feet deep, nearly captured by Waihee Canyon (1). Puu Kukui (2), the highest and wettest peak on West Maui, is in the background. The light-colored interstream flats (3) radiating from Kukui are peat bogs resting on Honolua lavas. Photo by U.S.A.A.F.

←

A long quiescent period followed when deep canyons were carved in the volcano, although a few eruptions may have occurred during this erosion interval. By the end of the cycle, the amphitheater heads of the canyons were several thousand feet deep, and apparently most of the canyons were cut back to the summit.

After this rest period, once more copious flows issued, along the southwest and east rifts only. These lavas partly filled the canyons and veneered most of the mountain except tracts adjacent to the northwest rift. This third and upper rock unit is the Hana volcanic series. Its lavas range in composition from ultrabasic olivine augite porphyries to nonporphyritic andesites.

During the early part of the last eruptive period, a voluminous mud flow, carrying blocks of consolidated cinders up to 50 feet in diameter, moved down Kaupo Valley to the sea. In the deep amphitheater heads of Kaupo and Keanae Valleys, flows and large cones of the Hana epoch practically masked the interstream divide between the adjacent canyons. The low interstream divide between Kaupo and Kipahulu Valleys still projects above this sea of lavas. Thus, the so-called crater of Haleakala is chiefly, if not entirely, the result of erosion by Kaupo and Keanae Streams, their two great amphitheaters coalescing to form the depression.[23]

Because so much of the surface of Haleakala Volcano has been covered by flows in Recent time, few traces of emerged shore lines remain. The oldest recognized gravels were apparently graded to a sea 95 feet higher than at present. Emerged fossiliferous marine deposits have been found up to 50 feet above sea level. Extensive lithified calcareous dunes lie on the Isthmus. The sand was blown inland when the sea stood about 60 feet lower in the late Pleistocene.

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[23] Stearns, H. T., Origin of Haleakala Crater, Island of Maui, Hawaii: Bull. Geol. Soc. America, vol. 53, pp. 1–14, 1942.

Opposite page: Plate 20. Fields of sugar cane on the slopes of the West Maui Mountains behind Lahaina. Photo by Hawaiian Airlines, Ltd.

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ISLAND OF KAHOOLAWE

Kahoolawe lies 7 miles off the south coast of Maui and 17 mile southeast of Lanai. It is 10.9 miles long, 6.4 miles wide, 1,427 feet high, and has an area of 45 square miles. Only a few families have lived on the island at one time, even in ancient days.[24] Now the only resident is a man who takes care of the cattle.

Kahoolawe is a single volcanic dome (pl. 21) composed of thin-bedded pahoehoe and aa basalt together with a few thin local beds of firefountain debris and several cinder cones, the largest being on the summit. These rocks including the associated intrusives are named the Kanapou volcanic series after Kanapou Bay where the type section is located. The higher parts of the island were once covered with deep lateritic soil, indicating that Kahoolawe is one of the older islands in the Hawaiian group. Overgrazing and strong winds have caused vast quantities of this soil to blow away.

The large, angular bay on the northeast coast exposes a great fault bounding the east side of a caldera 3 miles across and more than 800 feet deep. Subsequently this depression was completely filled with lava. A swarm of dikes running due east is exposed also in this cliff; and resting unconformably on its face, are five Recent cinder cones and flows. In the sea cliff forming the high south shore of the island, several faults are exposed. They apparently bound the south side of a graben which extended southwest from the caldera. The fault scarps were overflowed by lavas near the close of the dome-building epoch.

The island was built over three rifts (pl. 1), and two groups of lavas are distinguished in the Kanapou volcanic series, namely, (1) the pre-caldera lavas; and (2) the caldera-filling lavas, some of the upper members of which are slightly differentiated; five post-erosional lavas and pyroclastics of Recent age lie unconformably on the cliff at Kanapou Bay. Their distribution is shown in figure 16.

The valleys are partly drowned, indicating submergence; and the soil has been swept away by marine erosion to at least 800 feet above sea level.

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[24] McAllister, J. G., Archaeology of Kahoolawe: B. P. Bishop Mus. Bull. 115, p. 58, 1933.

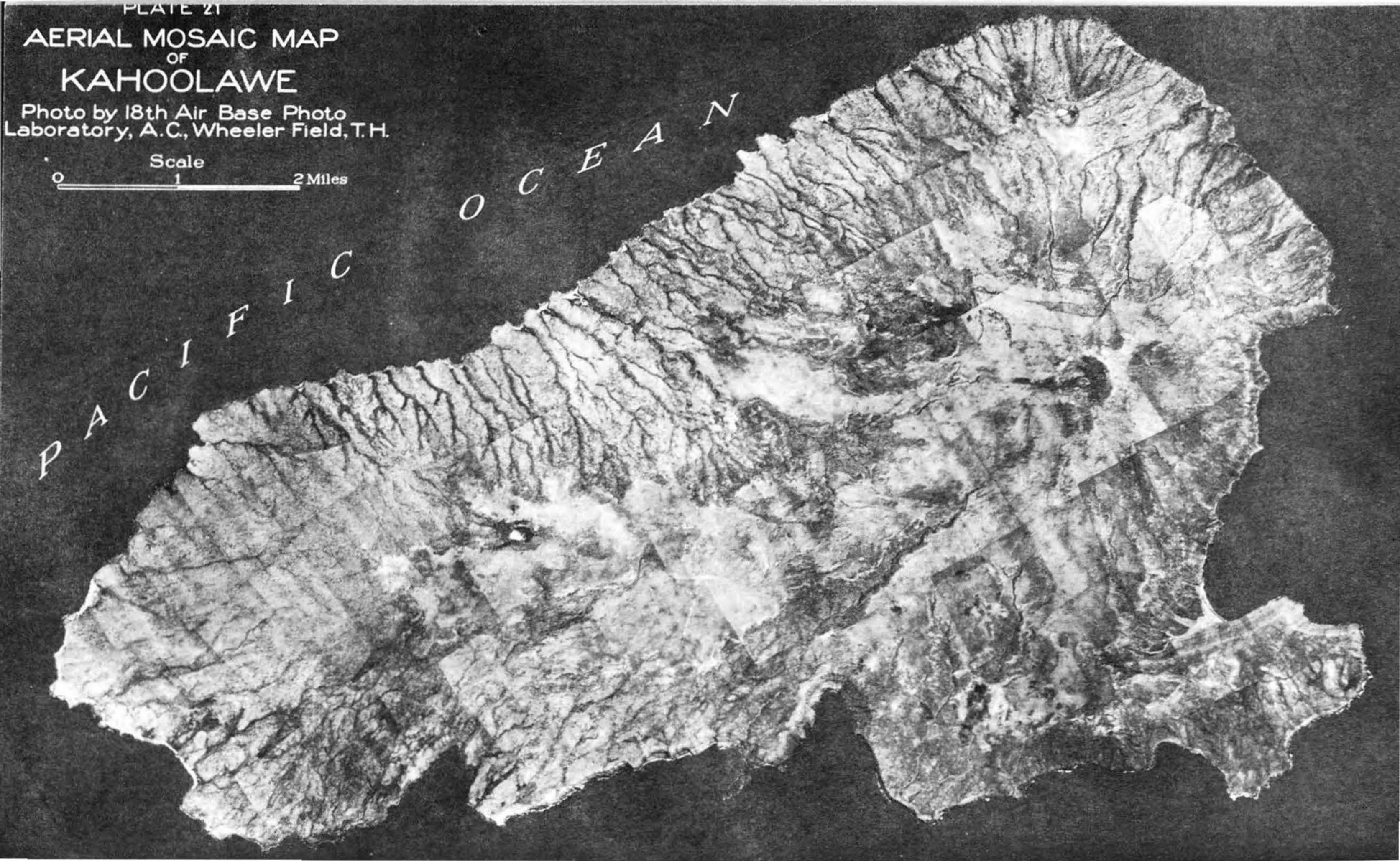
PLATE 21
AERIAL MOSAIC MAP
OF
KAHOOLAWE
Photo by 18th Air Base Photo
Laboratory, A.C., Wheeler Field, T.H.
Scale
0 1 2 Miles
PACIFIC OCEAN

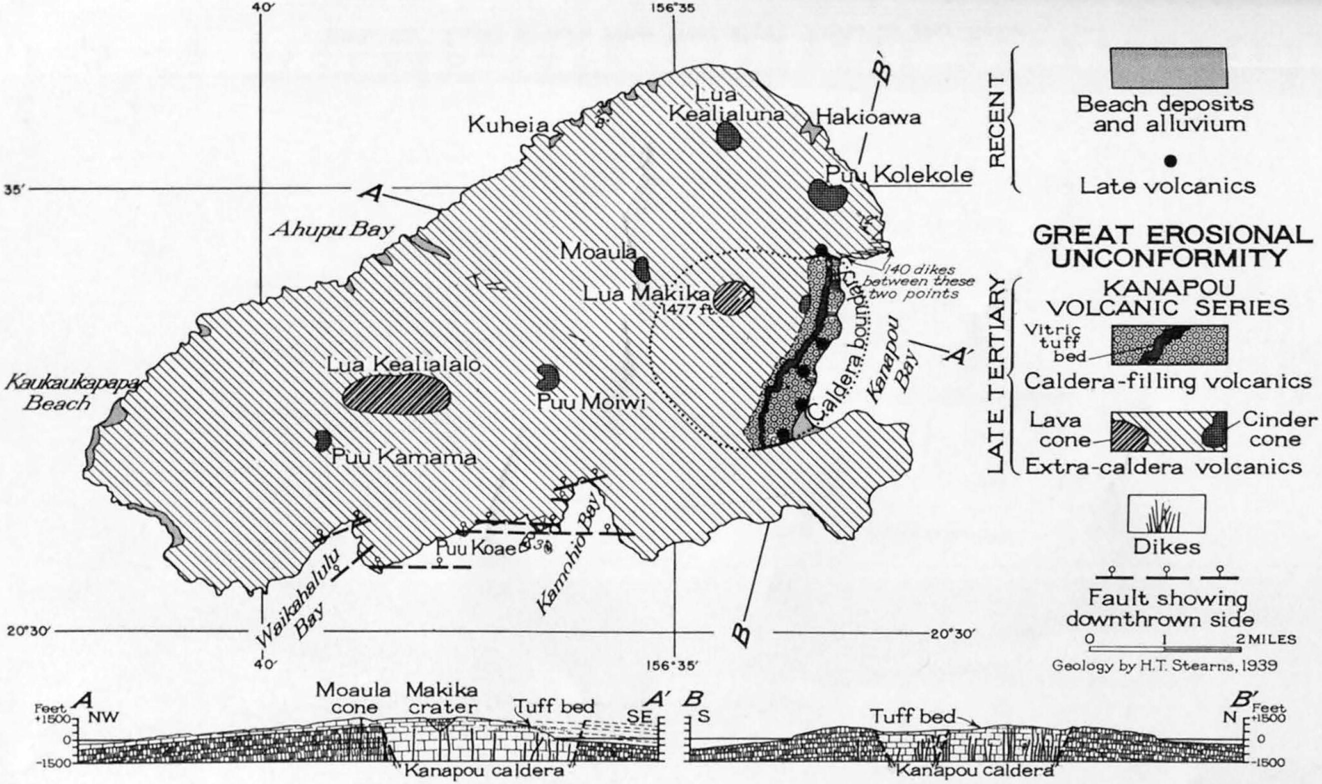

Figure 16. Geologic map and sections of the island of Kahoolawe. The extra-caldera volcanics include the post-caldera volcanics also.

Plate 22. Lanai as seen from West Maui. Photo by Ray Baker

Lanai consists of a single basaltic cone 3,370 feet high and about 13 miles across (pl. 22). Near the summit is Palawai Basin, the former caldera, which is approximately 3½ miles in diameter. It is now partly filled with alluvium and its formerly steep walls are smoothed by weathering and erosion. Lateritic soils 50 feet deep or more indicate that volcanic activity ceased probably in the late Tertiary. The volcano is built of thin-bedded aa and pahoehoe basaltic flows which, if not disturbed by faulting, dip 6° to 15°. Most of the lava welled out quietly from fissures and only a few mixed cinder and spatter cones were produced. Altogether about 375 feeding dikes are exposed, one of which contains ropy pahoehoe, and two, clinkery aa. These volcanic rocks comprise the Lanai volcanic series. The distribution of the rocks is shown in figure 17.

The volcano was built over a northwest rift zone, a southwest rift zone, and a south rift zone which intersect at the summit (pl. 1). After a long, uninterrupted period of extrusion the northwest and south rifts collapsed to produce the grabens which radiate from the caldera. At the same time, fault scarps more than 1,000 feet high were formed, and much rock was shattered. More than 100 fault traces are now exposed on Lanai. One of the high fault scarps shielded the whole northeast segment of the dome from lava flows of later date, and deep canyons were eroded on this slope.

The volcano was extinct long enough for thick lateritic soil to form, then the island passed through a series of Pleistocene submergences and emergences similar to those of Oahu. Because of aridity, many of the emerged shore lines are well preserved; and the highest fossiliferous marine conglomerate known in the Hawaiian Islands is 1,070 feet above sea level on the south side of the island. Below an altitude of 1,200 feet, much of the soil has been removed by marine erosion, and the surface is a bare, rocky scabland. At an altitude of 560 feet, an excellent shore line can be traced around the island by the benches and fossiliferous conglomerates; and at several lower levels, still other former strand lines can be observed.[25] Lithified calcareous dunes blown inland during the last Pleistocene low stand of the sea crop out in a narrow strip to an altitude of 950 feet.

High marine cliffs were not cut during submergence; but when the sea stood below the present ocean level, most of the south and west coasts were cliffed, in some places to heights of 1,000 feet.

Lanai has been extinct longer than any of the other main islands. The islands of Niihau, Kauai, Oahu, Molokai, Maui, Kahoolawe, and Hawaii have had secondary eruptions in late Pleistocene or Recent time.

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[25] Stearns, H. T., Ancient shore lines on the island of Lanai, Hawaii: Geol. Soc. America Bull., vol. 49, pp. 615–628, 1938.

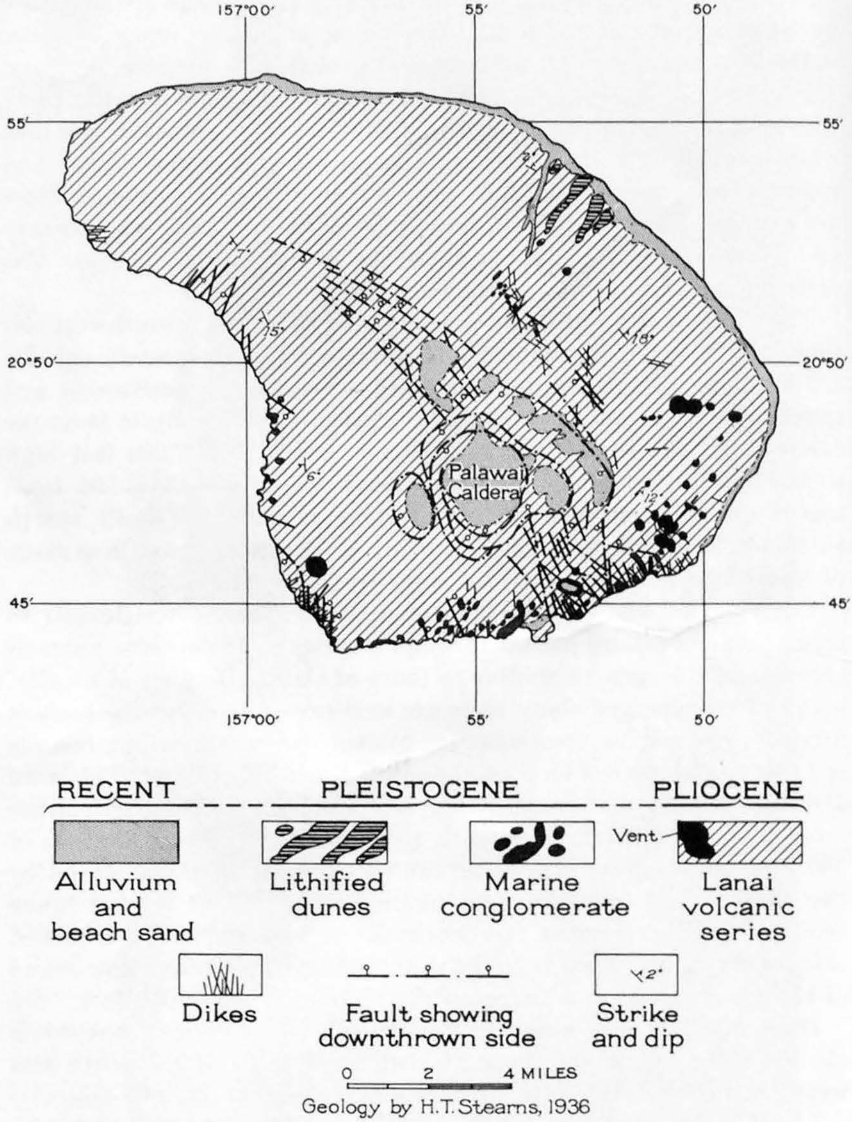

Figure 17. Geologic map of the island of Lanai.

Three volcanoes built Molokai. The western one, known as West Molokai, is 1,381 feet high and about 12 miles across. The eastern one is called East Molokai Mountain. This volcano is 4,970 feet high, 27 miles long from north to south, and 8 miles wide from east to west. A smaller and much later volcano forms the Kalaupapa Peninsula on the north coast of the eastern volcano. The stratigraphic rock units on the island are given in the accompanying table and their distribution is shown in figure 18.

Stratigraphic rock units on the island of Molokai

Age	Rock assemblage	
	Sedimentary rocks	Volcanic rocks
Recent	Younger alluvium and unconsolidated beach and dune deposits	
Pleistocene	Lithified dunes, emerged reef limestone, and older alluvium	Kalaupapa basalt
Great erosional unconformity		
Tertiary		East Molokai volcanic series: Upper (andesite) member; Lower (basalt) member; Caldera complex member Erosional unconformity West Molokai volcanic series

West Molokai.—Most of West Molokai is covered with lateritic soil 10 to 50 feet thick, indicating long extinction. The former center of volcanic activity lies just south of the summit and is barely exposed in a narrow gorge draining the area. Most of the lava was extruded from a rift zone which extends 10 miles to the southwest and plunges under the sea. Penguin Bank, the most extensive submarine shelf adjacent to the main islands, stretches 27 miles to the southwest of Molokai (pl. 1). The average depth of water over the bank is about 180 feet. At the edge of the shelf is a sheer submarine cliff 1,800 to 3,600 feet high. This bank trends southwestward along the submarine extension of the southwest rift zone of West Molokai and, therefore, may be a marine platform which was planed across the rift zone ridge during a low stand of the sea. A veneering reef may also exist. Another explanation is that the bank was originally a separate volcano leveled by the sea and possibly capped by coral reef. If there was an older volcano, then possibly West Molokai was built on the northeast rift zone of that mountain.

Opposite page: Plate 23. The great cliff on the north side of East Molokai. The peninsula in the foreground is Kalaupapa Volcano which is younger than the cliff. Note the dikes forming walls in the right foreground. Photo by U. S. Navy.

←

West Molokai consists almost entirely of thin-bedded aa and pahoehoe basalt flows, named the West Molokai volcanic series. The volcano has a flatter dome than most of the others in the Hawaiian group. A few eroded and weathered cinder and spatter cones lie on the rifts.

On the east side are numerous fault flocks indicating collapse of the northeast slope. The most prominent scarp is 500 feet high.

In the gulch draining southward from the main vent, the West Molokai lavas, covered with 3 feet of lateritic soil and underlain by 6 feet of spheroidal weathered basalt, can be seen passing under the flows from the eastern volcano. Therefore, West Molokai Volcano must have become extinct a long time before its large eastern neighbor.

Most of the lower slopes are covered with the shingle of former beaches—the surface having been swept bare of lateritic soil. These indications of former high sea level have not yet been studied in detail. Calcareous dunes which have migrated inland for 4 miles cover a tract of about 2 square miles on the western part of the windward (northeast) side. Some of these dunes are lithified, and, along the northwest end of West Molokai, extend into the ocean at the foot of a nearly vertical marine cliff about 500 feet high. Obviously, the cliff was cut during a low stand of the ocean which preceded another fall of sea level when the dunes were formed. Further study will probably show a series of emergences and submergences similar to those on Oahu and Lanai.

EAST MOLOKAI.—The large eastern dome is cut into great amphitheater-headed valleys on the windward side and smaller ones on the leeward side. A spectacular cliff, reaching a maximum height of 3,600 feet, forms the entire north coast of the mountain (pl. 23). Faulting may have played a part in the origin of this cliff.

A survey of the heads of Wailau and Pelekunu valleys revealed that these valleys tapped a caldera about 4 miles across and that the size of their amphitheater heads is only partly attributable to erosion.[26]

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[26] Stearns, H. T., Large caldera on the island of Molokai, Hawaii: Geol. Soc. America Proc. 1937, p. 116, 1938.

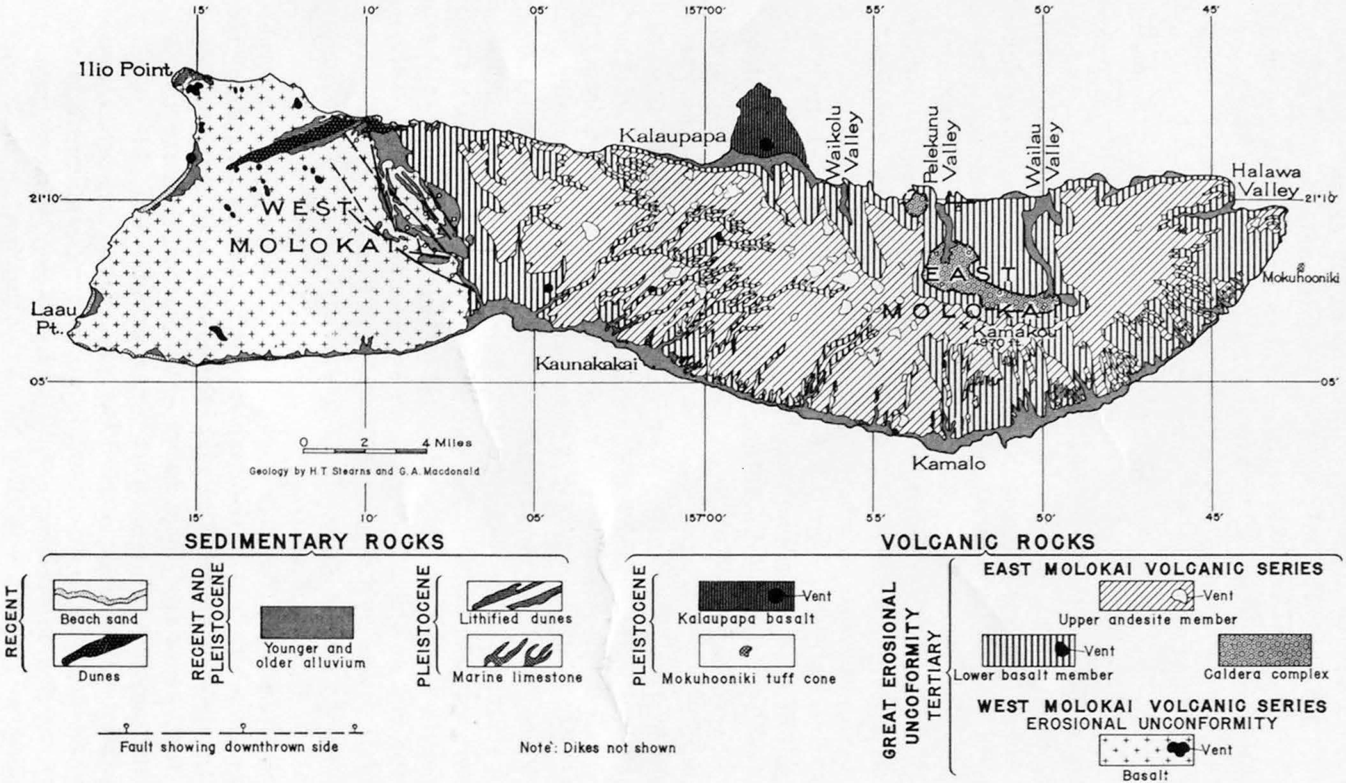


Figure 18. Geologic map of the island of Molokai.

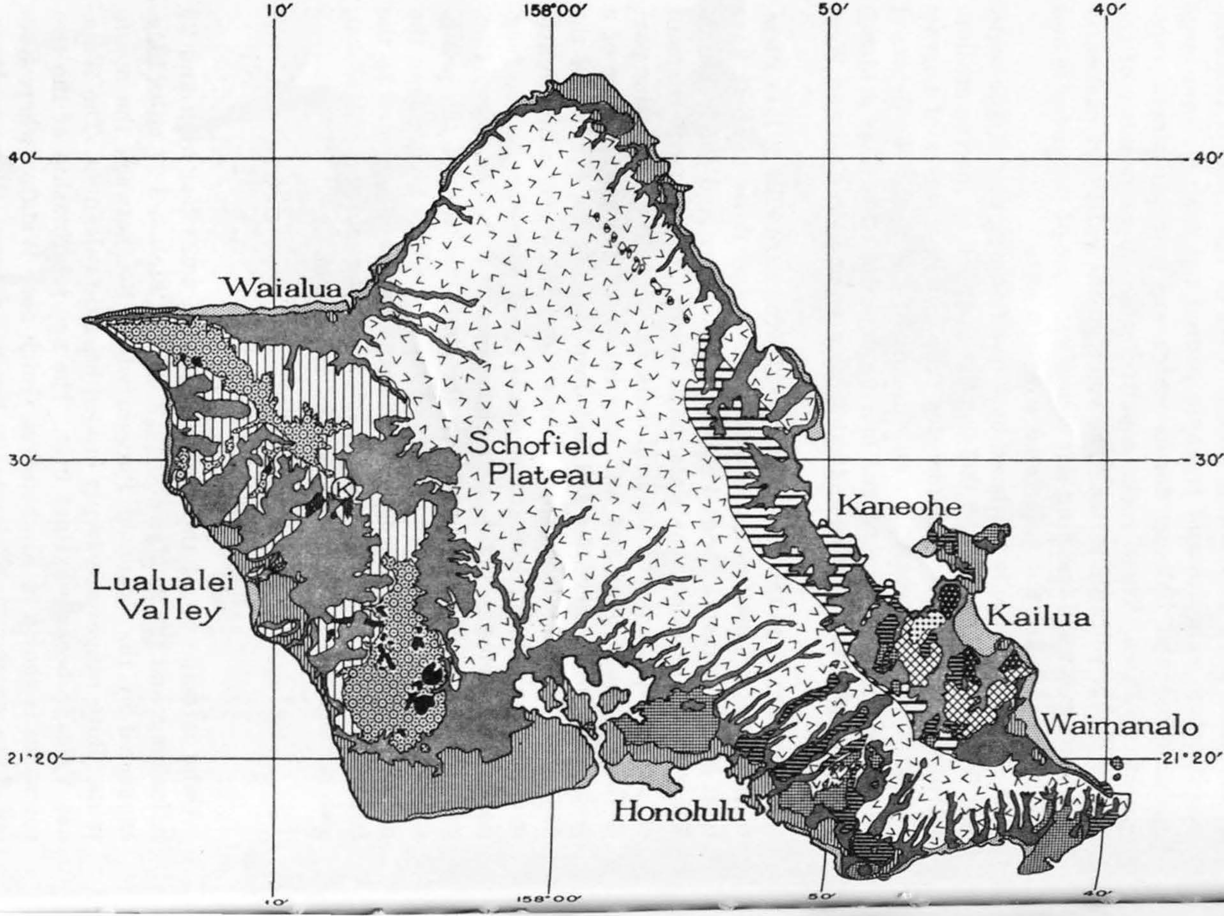
This volcanic dome is composed chiefly of thin-bedded basaltic aa and pahoehoe having an average dip of about 12° except where the flows bank against West Molokai. They constitute the lower member of the East Molokai volcanic series. Most of the dome is veneered by oligoclase andesite and trachyte poured out mainly from large cinder cones and bulbous domes which are now prominent topographic features. These rocks constitute the upper member of the East Molokai volcanic series. The volcano was built over eastward- and northwestward-trending rift zones, but some of the andesite and trachyte cones are not associated with the rifts.

The leeward shore is bordered by a live fringing reef a mile wide, and the slopes above it for 1,000 feet are stripped by marine erosion. Fossiliferous marine conglomerates crop out in a series of narrow discontinuous terraces up to an altitude of 280 feet. The drowned windward valleys and emerged marine deposits offer clear evidence of the complex emergences and submergences on both East and West Molokai.

KALAUPAPA.—At the foot of the great windward cliff in late Pleistocene time, a small volcano was formed, and flows from it have built a low peninsula about 4 square miles in area and 405 feet high. These lavas are named the Kalaupapa basalt. The Leper Settlement called Kalaupapa lies on the peninsula (pl. 23). The submarine part of the volcano is huge and well may represent the young stage of a great new dome. A crater 400 feet deep indents the summit of the dome. Some of the loose coral debris along the shore is apparently in a higher position than storm waves could have thrown the fragments, and seems to indicate an emergence of 5 feet or more. Conglomerate overlying the basalt on the southeast side of the peninsula seems to be graded to a stand of the sea 25 feet higher than the present. On this evidence the Kalaupapa basalt is assigned to the late Pleistocene. Mokuhooniki, an island off the east end of Molokai, also belongs to this renewed epoch of volcanism.

ISLAND OF OAHU

Oahu is made up of the Waianae Range, 4,025 feet high and 22 miles long, and the Koolau Range, 3,105 feet high and 37 miles long, connected by the Schofield Plateau which lies between the mountains. Both ranges are deeply eroded basaltic volcanoes. The Waianae Volcano became extinct first. The age relationship of the two volcanoes is shown in Kaukonahua Gulch near Waialua where Koolau flows overlap unconformably the soil-covered Waianae lavas. The rock units on Oahu are given in the accompanying table and their distribution is shown in figure 19. Eight stages in the geologic history of Oahu are shown in plates 3 to 6.


10′
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Waialua
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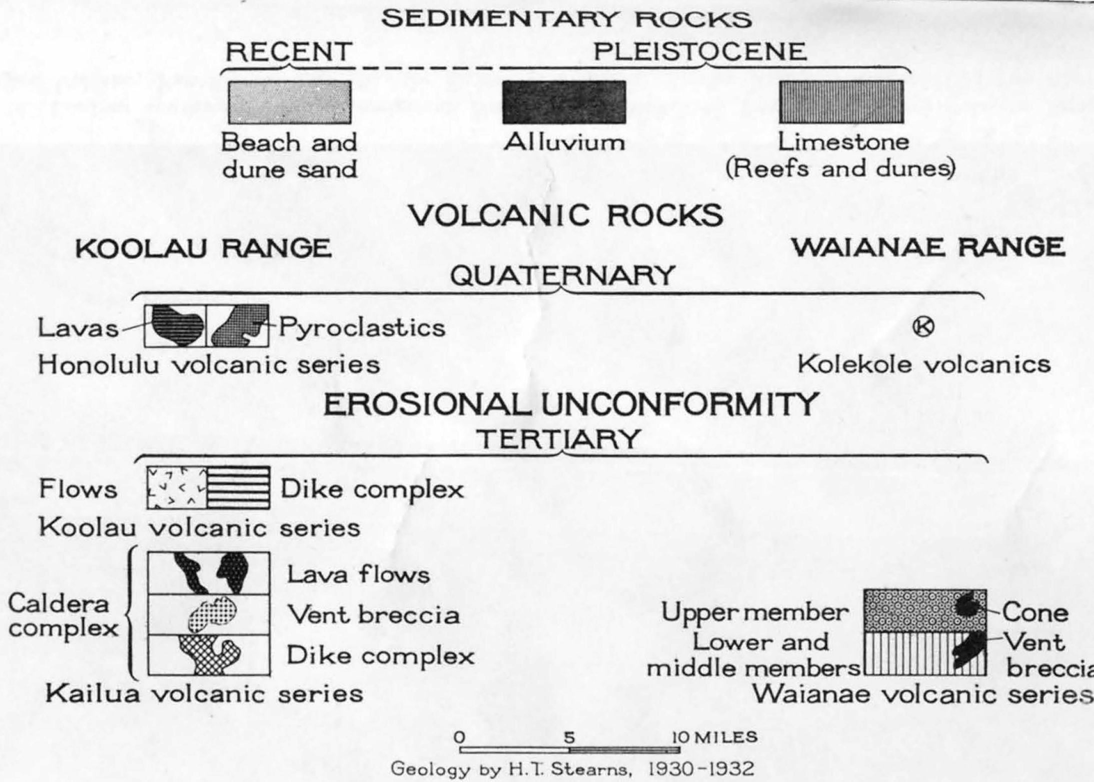

Figure 19. Geologic map of the island of Oahu. Faults and dikes omitted.

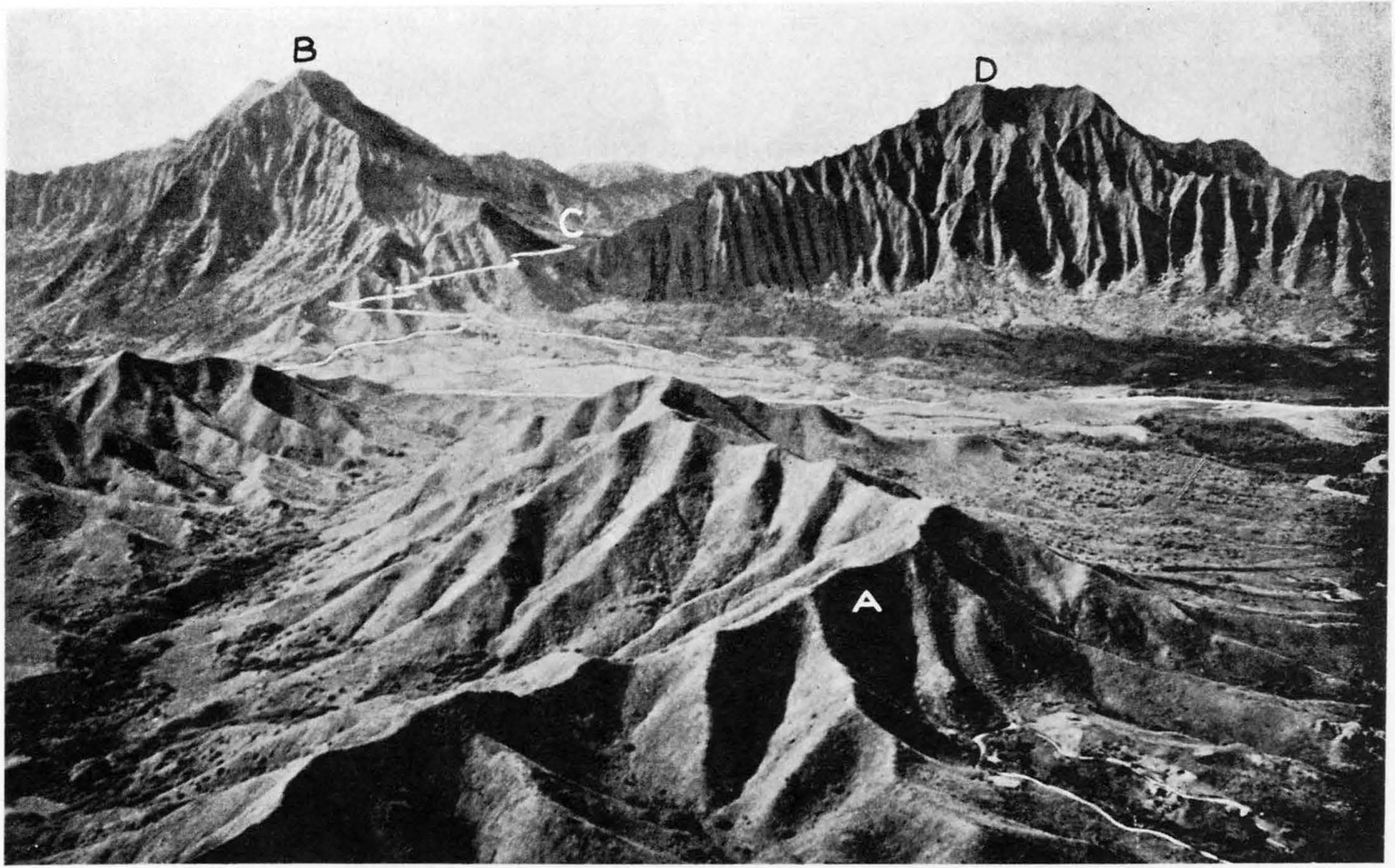

Plate 24. Looking southwest toward precipitous Nuuanu Pali. Kokokahi Peak (A), a root of the former firepit of Koolau Volcano; Puu Konahuanui (B), the highest peak of the Koolau Range; *Pali gap* (*C*); *Puu Lanihuli* (*D*). Photo by U.S.A.A.F.

Waianae Range.—The Waianae Range is composed of three groups of lavas erupted in Tertiary and possibly in early Pleistocene time from three rift zones (pl. 1). The exposed part of the oldest lava is nearly 2,000 feet thick and consists largely of thin-bedded pahoehoe. In most places an angular unconformity and talus breccia, and in a few places, an erosional unconformity, separate the middle lavas from the first series. The middle basalts are about 2,000 feet thick and closely resemble the lower ones except that the later beds contain more aa. The upper lavas are about 2,300 feet thick and are mostly massive aa andesite flows which issued from large cinder cones.

A few secondary eruptions also occurred on the Waianae Range during the Pleistocene near the ancient caldera.[27] These lavas and cinders are deeply weathered and nearly cut away by erosion. They crop out near Kolekole Pass and are named the Kolekole volcanics. They are probably correlative with the secondary eruptions on the Koolau Range. The Waianae Volcano, like most of the others in the islands, produced only small amounts of ash, and most of the lavas were extruded from fissures a few feet wide, now indicated by dikes. The caldera complex near Kolekole Pass, at the head of Lualualei Valley, was the center of volcanic activity. A trachyte flow 400 feet thick crops out in Lualualei Valley and is being used for the manufacture of Portland cement. It is in the middle member.

[27] Stearns, H. T., Supplement to the geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. Hydrography Bull. 5, pp. 47-48, 1940.

Stratigraphic rock units on the island of Oahu

Age	Rock assemblage	
	Sedimentary rocks	Volcanic rocks
Recent	Coral fills, younger alluvium, and unconsolidated beach and dune sand	Younger members of the Honolulu volcanic series
Pleistocene	Older alluvium, lithified dunes, and emerged marine limestones chiefly coralliferous	Older members of the Honolulu volcanic series and the Kolekole volcanics
Great erosional unconformity		
Pliocene		Koolau and Kailua volcanic series Erosional unconformity Waianae volcanic series: Upper member; Middle member; Lower member

KOOLAU RANGE.—The lavas of the Koolau Volcano were extruded in Tertiary time from three rift zones (pl. 1). They belong to two groups. One, the Kailua volcanic series, is greatly altered by hydrothermal action and its vesicles are filled with quartz, zeolites, and other minerals.[28] These lavas and their feeding dikes are exposed only near Kailua, where the beds are 600 feet thick; however, no contact could be found between these lavas and those of the Koolau volcanic series. This second group is not altered and makes up the greater part of the Koolau Range. The Kailua lavas are believed to have accumulated in the caldera of the Koolau Volcano.

Two large masses of vent breccia adjacent to the Kailua lavas, indicate that the caldera of the Koolau Volcano was several miles across and occupied much of the area between Waimanalo and Kaneohe. Most of the lava was extruded from the northwest rift zone as is shown by the extension of the island in this direction. The flows of the Koolau volcanic series have an exposed thickness of about 3,000 feet and consist of thin-bedded pahoehoe and aa with inappreciable amounts of ash. Only two small cinder cones were found in this series. Practically all the lavas were erupted from narrow fissures unaccompanied by large lava fountains.

During the Pleistocene large parts of both the Waianae and Koolau Ranges were removed by fluvial and marine erosion. The unusual physiographic feature of Oahu is the loss through fluvial erosion of much of the leeward side of the Waianae Volcano, whereas large parts of the rainy or windward side remain. This anomaly is explained on page 5.

The master streams of the Koolau Range have deep amphitheater-headed valleys. During the erosion cycle, a large part of the windward slope was eroded away by streams. The great "Pali," or northeast cliff, of the Koolau Range is the result of two processes (pl. 24). First, the amphitheater-headed valleys ate headward and a little beyond their divides, and second, most of the interstream divides were buried through alluviation which accompanied the deep submergence of the islands.[29]

After the two ranges were sculptured by fluvial and marine erosion into essentially their present form, the island went through a complicated series of emergences and submergences. Data from well logs show that the valleys have been drowned at least 1,200 feet; and the island may still be submerged nearly 1,800 feet, if the submarine

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[28] Dunham, K. C., Crystal cavities in lavas from the Hawaiian Islands: Am. Mineralogist, vol. 18, no. 9. pp. 369–385, 1933.

[29] Stearns, H. T., and Vaksvik, K. N., Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. Hydrography Bull. 1, pp. 26–29, 1935.

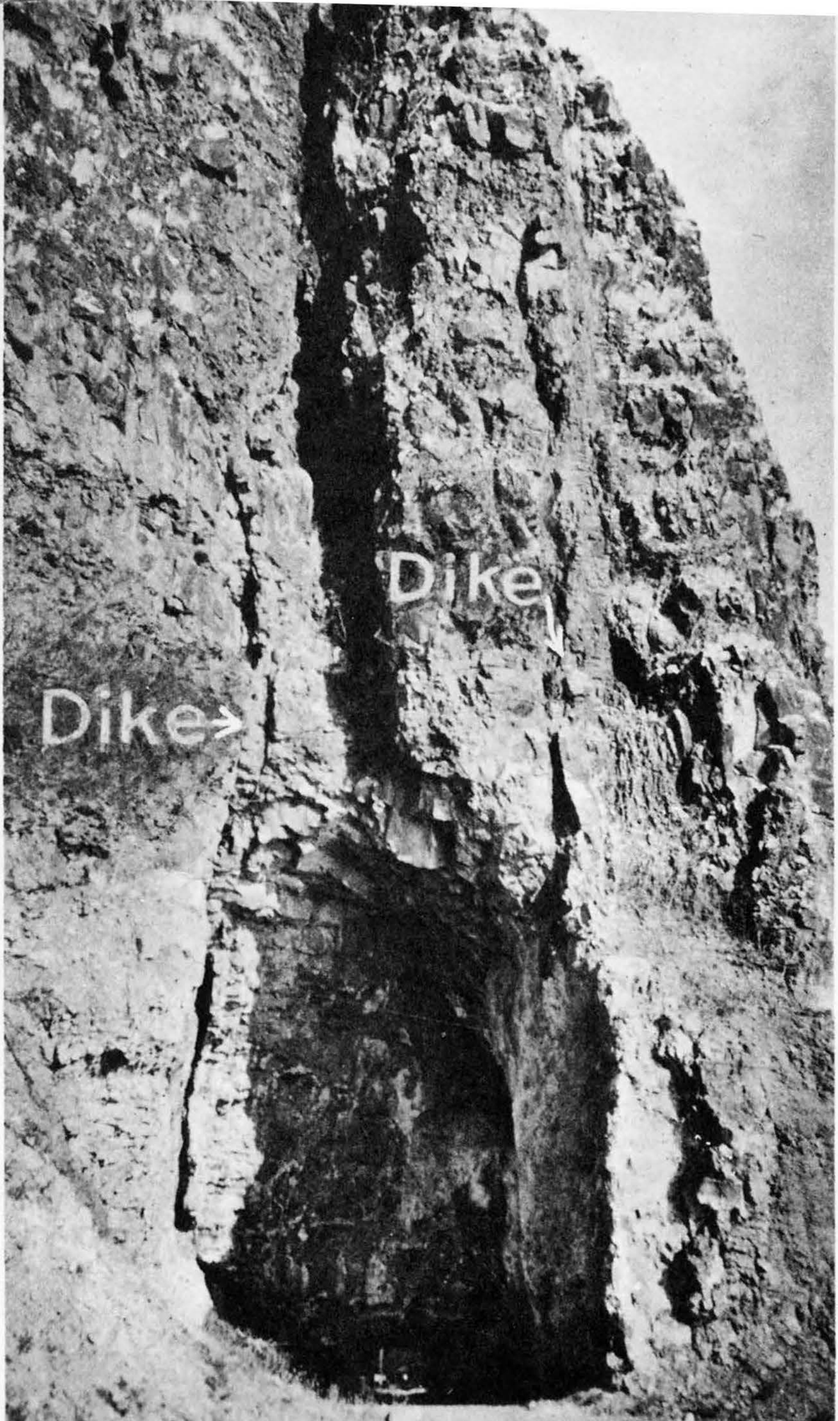

Plate 25. Makua Cave, Oahu Island. Photo by the author.

Plate 26. The youthful Kaau Crater indents the rugged topography of the Koolau Range. Photo by U.S.A.A.F.

shelf at that depth around Oahu was originally a shallow water platform. Further, the slopes of the island show evidence of marine action several hundred feet above sea level indicating an even greater submergence in the past. Apparently the emergence was not continuous for a halt is suggested at 560 feet as well as at several lower levels. Unconformable emerged marine deposits, well logs, and a submarine shelf at 50 fathoms, all indicate that the ocean receded to about 300 feet below the present strand. Again the ocean rose 95 feet above sea level and left a well-marked shore line and some emerged reef. Another regression with minor halts stopped about 60 feet below sea level, and was followed by a transgression that rose 25 feet above the present strand. During the last emergence of the island, the sea halted for a short time about 5 feet above the shore line, then established its present level. In addition to the terraces, wide areas of emerged reef limestone (fig. 20), abandoned sea caves

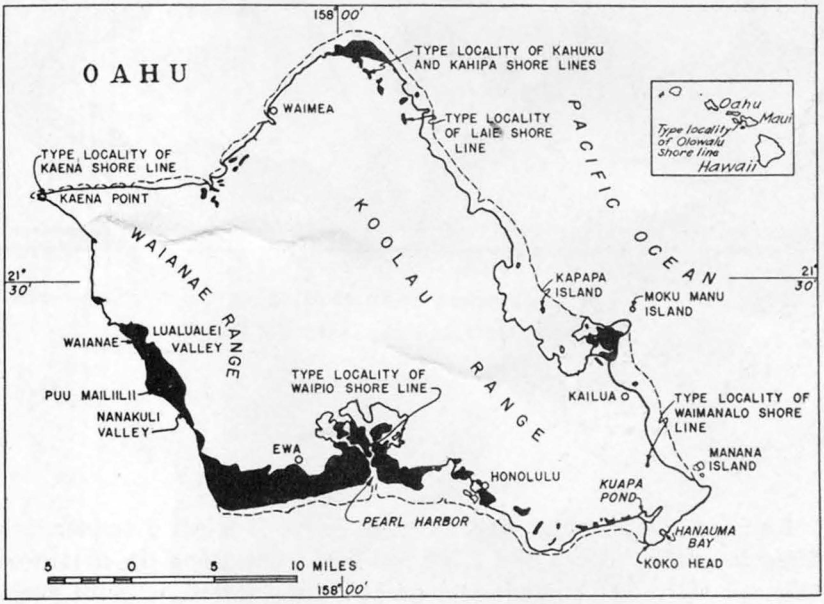

Figure 20. Map of Oahu showing areas of emerged reefs (solid black) and fringing reefs (dotted line shows outer edge).

(pl. 25), bear witness to the changing relationships of land and sea.

Concomitant with the shifting of ocean levels, spasmodic eruptions at the southeast end of the Koolau Range produced many lava flows and cinder and tuff cones, most of which are nepheline basalt (fig. 21 and pl. 26). These are the Honolulu volcanic series. The last eruption was in Recent time. The contact of magma with ocean or ground water apparently caused many explosions which resulted in the only tuff cones on the island. Many of the later flows and pyroclastics are interstratified with alluvium and marine sediments.

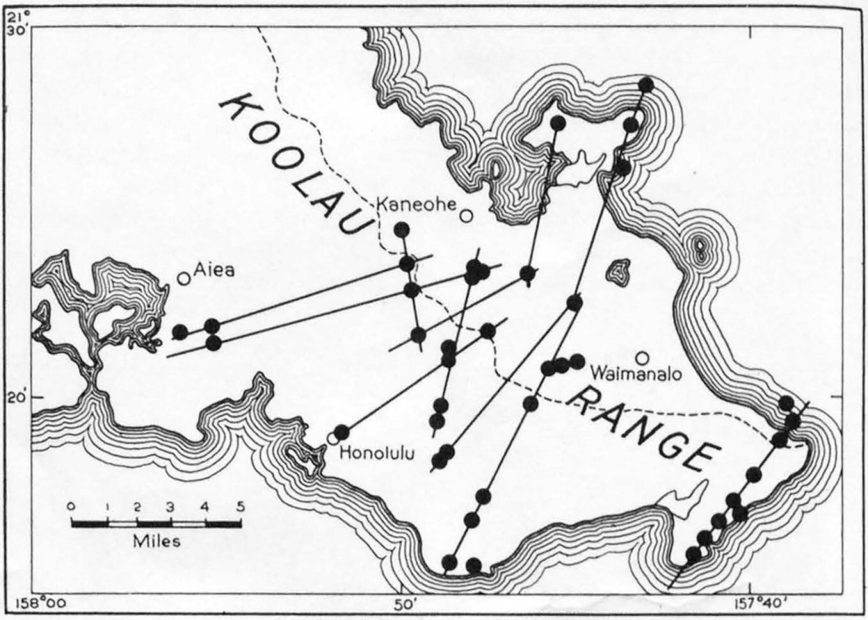

Figure 21. Map of southeastern Oahu showing secondary post-Koolau volcanic vents and dominant rift trends.

ISLAND OF KAUAI *

Kauai, 5,170 feet high and 32 miles in its greatest diameter, is a dissected dome. A sea cliff 2,700 feet high runs along the northwest side (pl. 27). The summit is a great swamp where, in some years, the precipitation is more than 500 inches. Hinds spent most of nine months on Kauai and made the only previous detailed study of the island.[27] He did not make a geologic map however, and most of his major observations cannot be verified in the field.

[27] Hinds, N. E. A., The geology of Kauai and Niihau: B. P. Bishop Mus. Bull. 71, 103 pp., 1930.

*See Supplement for revisional comments on text. Map on page 83 and table on page 85 supersede those in First Printing.

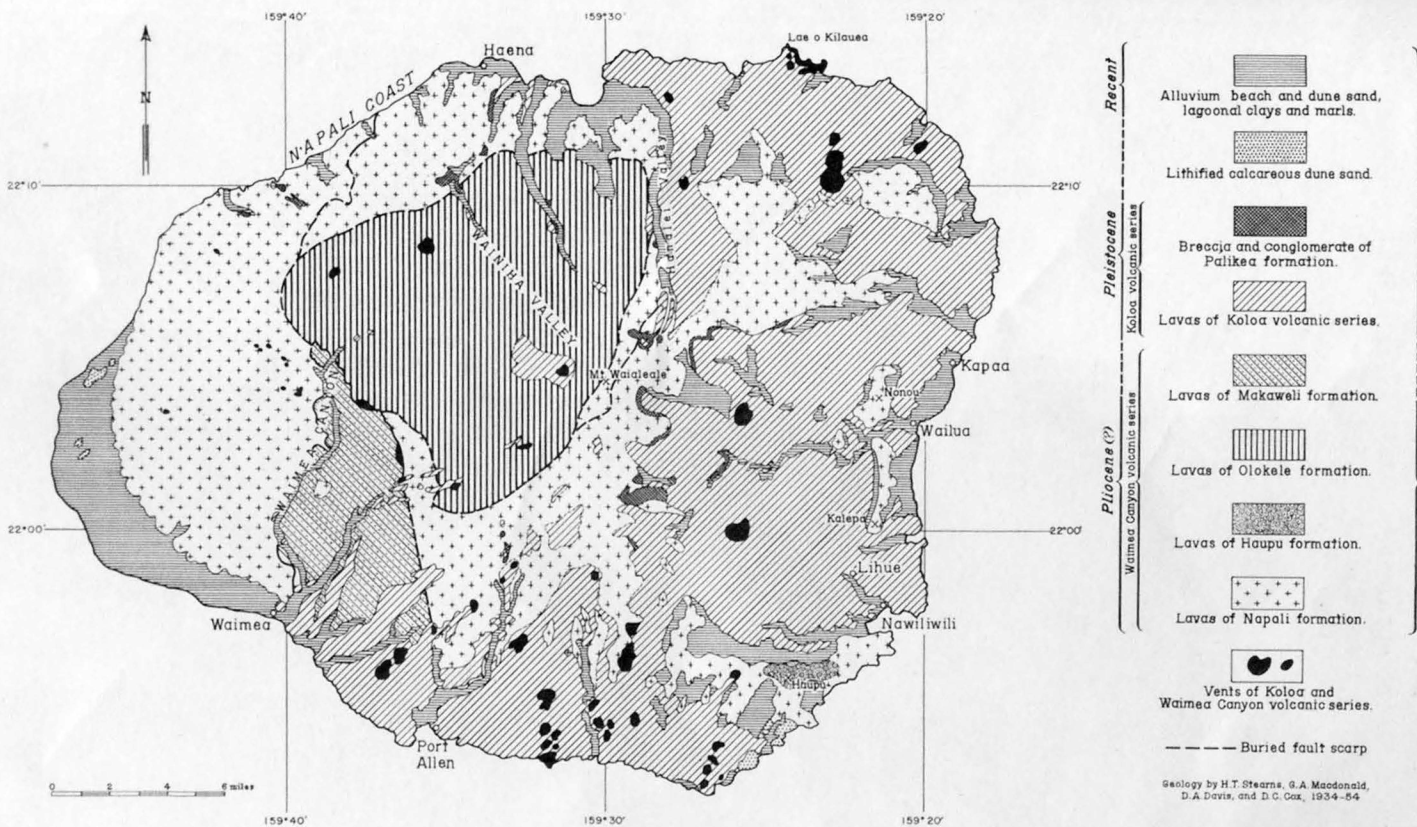

Figure 22. Geologic map of the island of Kauai, dikes omitted.

Opposite page: Plate 27. Looking northeast along the Napali Coast of Kauai. The large valley is Kalalau. Photo by U.S.A.A.F.

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The geology is complex and is now being investigated. Because of the lack of data, rifts are not shown on plate 1, but it is known that many radial dikes exist. During a reconnaissance in 1934, a profound angular unconformity was discovered at the head of Waiahulu Gulch, a tributary of Waimea Canyon, and another was found in Olokele Canyon. In the Waiahulu unconformity, the lavas on the southwest side are older than those on the northeast side and in places are separated by talus. This unconformity is the fault escarpment forming the southeast wall of a great summit caldera about 10 miles across. The lavas on the northeast are the massive, nearly horizontal type which result from ponding in a caldera. The principal rock units are given in the accompanying table and their distribution is shown in figure 22.

Stratigraphic rock units on the island of Kauai

Age	Rock assemblage		
	Sedimentary rocks	Volcanic rocks	
Recent	Beach and dune sand and alluvium		
	Local uncomformity		
Pleistocene	Older alluvium and lithified dune sand; lagoon deposits of Mana Plain	Koloa volcanic series: aa and pahoehoe lava flows of nephelinite, picrite-basalt, basanite, and alkalic olivine basalt, with some intercalated ash and tuffaceous soil beds, cinder cones at the vents, and a tuff cone at Kilauea Bay	
	Local unconformity		
	Palikea formation: poorly sorted breccia and poorly to moderately sorted conglomerate at the base of, and intercalated with, the rocks of the Koloa volcanic series		
	Major erosional unconformity		
Pliocene	Mokuone member of the Makaweli formation: poorly sorted breccia at the base of, and moderately sorted conglomerate interbedded with, the lavas of the Makaweli formation	Waimea Canyon volcanic series: tholeiitic basalt, olivine basalt, and oceanite lavas, with a little hawaiite (andesine andesite) in its uppermost part	Makaweli formation: aa and pahoehoe lava flows accumulated in a graben on the southwest side of the Kauai shield volcano Olokele formation: thick massive flows accumulated in a broad caldera at the summit of the Kauai shield volcano Haupu formation: thick massive flows accumulated in a large pit crater on the southeast slope of the Kauai shield volcano Napali formation: thin-bedded pahoehoe and aa flows forming the Kauai shield volcano and dipping outward at angles of 5-10° in all directions from the caldera boundry

The main bulk of Kauai is a deeply eroded shield-shaped volcano or dome with its associated intrusives, breccias, and thin vitric tuff beds. These rocks comprise the Waimea volcanic series and were erupted in the Tertiary. The extra-caldera or lower member is composed of more than 3,500 feet of thin-bedded primitive-type olivine basalts dipping 5° to 20° away from the ancient caldera (pl. 28). The caldera-filling or upper member is composed of 4,000 feet of chiefly horizontal and massive olivine basalts (pl. 28) laid down in

Opposite page: Plate 28. Waimea Canyon, Kauai. The lavas on the left belong to the lower member and the horizontal bedded ones in the background belong to the upper member of Waimea volcanic series. The horizontal lava beds in the bottom of the canyon and forming the right wall belong to the Koloa volcanic series. Photo by U. S. Navy.

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the summit caldera. The high Waialeale plateau is underlain by these rocks. A few basaltic andesites are present at the top of this member. The upper and lower members are separated by partly exhumed fault scarps more than 3,000 feet high and talus breccia.

The Haupu volcanic series forms Haupu (Hoary Head) Ridge near Lihue (pl. 29). It is composed of an extra-caldera or lower member of thin-bedded primitive-type olivine basalts dipping 8° to 15° away from the central vent and an upper member of horizontal massive basalts filling a caldera 1½ miles across. The upper and lower members are separated by a partly exhumed fault scarp and talus breccia. The Haupu volcanic series is the remains of an independent volcano about 2,300 feet high on the side of the ancient Waimea Volcano, and is similar to the position of Kilauea Volcano to Mauna Loa Volcano.

The rocks of the Waimea and Haupu volcanic series are separated everywhere by a deep zone of weathering and a great angular erosional unconformity from a third unit, named by Hinds, the Koloa series. The Koloa volcanic series is composed of olivine basalts, and ultrabasic rocks carrying nepheline and melilite. The flow near the mouth of Waimea Canyon carries log molds in pillow lava.[30] The Koloa volcanic series are correlative in composition, stratigraphic position, and age to the Honolulu volcanic series on Oahu, but are much more voluminous. They built a broad plain between Koloa and Kapaa. Kilohana Crater is one of the largest vents. Most of the vents lie on north-south rifts. The cycle of renewed activity when they were erupted was fairly long for in Hanapepe Canyon two sets of intercanyon lavas crop out separated by a profound erosional unconformity. Similar unconformities exist elsewhere on Kauai.

Hinds[31] reports conglomerates between lavas in Koaie and Poomau tributaries of Waimea Canyon and states that they indicate a great erosion interval during the accumulation of the lavas in the early Kauai dome, or in the Waimea volcanic series. The lava overlying the conglomerate is a flow belonging to the Koloa volcanic

[30] Stearns, H. T., Pillow lavas in Hawaii: (abst.) Geol. Soc. America Proc. for 1937, pp. 252–253, 1938.
[31] Idem, p. 56.

series; hence is not evidence of an erosional interval in the Waimea series. Clark describes the line of vents from which these Koloa lavas issued.[32]

The Koloa volcanic series have greatly affected the course of streams and built extensive plateaus at the mouths of the major valleys. The so-called elevated marine plain at 500 feet above sea level described by Hinds[33] is not a marine plain but a series of plateaus built by lavas of the Koloa volcanic series. Hitchcock[34] thought the plain was built of young ashes instead of lava. The hills near Wailua do not outline a great caldera north of Lihue as Hinds thought.[35] Instead, they are erosional remnants of the lower member of the Waimea volcanic series nearly buried by lavas of the Koloa series as shown by the dip and character of the lavas in them. The ancient Waimea dome was deeply dissected by great amphitheater-headed valleys similar to those in the Waianae Range, Oahu Island, but the floors and some of the interstream divides have been buried by the copious Pleistocene lavas. Only Wainiha Valley retains essentially its original form.

The great sea cliff 2,700 feet high forming the scenic Napali coast (pl. 27) is not a fault scarp as commonly supposed. It was caused by marine erosion battering back, as the island submerged, the interstream divides composed of the weak lavas in the lower member of the Waimea volcanic series. Between Haena and Kalalau Valley, where the highest part of the coastal cliff lies, the lower member was cut away and the sea was arrested by the massive wave-resisting upper member of the series. This part of the coast is an obsequent fault-line scarp and is due to the difference in strength of the rock in the caldera and extra-caldera member of the Waimea volcanic series. The ancient fault dips southeastward away from the coast rather than northwestward into the sea (fig. 23).

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[32] Clark, W. O., Geology of the island of Kauai (abst.) : Geol. Soc. America Proc. for 1934, p. 72, 1935.

[33] Idem, p. 35.

[34] Hitchcock, C. H., Hawaii and its volcanoes, p. 13, 1909.

[35] Idem. p. 36.

←

Opposite page: Plate 29. Haupu (Hoary Head) Ridge and Nawiliwili Harbor, Kauai. The lavas in the ridge belong to the Haupu volcanic series. The lavas underlying the sugar cane fields belong to the Koloa volcanic series. Photo by Hawaiian Airlines, Ltd.

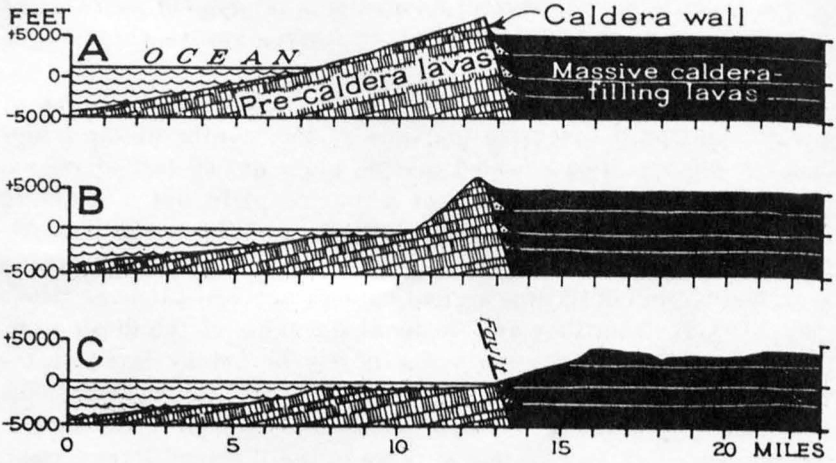

Figure 23. Sections showing the development of the Napali Cliff, Kauai. A. At close of volcanism. B. After stream erosion had carved valleys in the weak pre-caldera lavas. C. Present stage, an obsequent fault-line scarp caused by the resistance of massive caldera-filling lavas to wave erosion.

Waimea Valley is described by Hinds[36] as due to faulting. Although the position of Waiahulu tributary was determined by a fault, Waimea Canyon from the mouth of this fork to the sea owes its position to displacement westward by lava flows of the Koloa volcanic series (fig. 22). Waimea Canyon owes its large size to the fact that it drained the major part of the summit caldera where the rainfall is even now in excess of 450 inches per year.

ISLAND OF NIIHAU

Niihau, 17½ miles southwest of Kauai, is 18 miles long, 6 miles wide, and has an area of 72 square miles. It is 1,281 feet high and consists of an eroded upland skirted on the north, west, and south sides by a coastal plain. The east and northeast sides of the upland are bounded by a high sea cliff. The climate is semiarid. No living streams exist but playa lakes are numerous.

The stratigraphic rock units on the island are given in the accompanying table and their distribution is shown in figure 24. The main mass of the island is composed of the Paniau volcanic series, which constitutes a deeply weathered remnant of a Tertiary basalt dome cut by a dike complex trending NE-SW. The dikes are well exposed

[36] Idem, fig. 13.

in the eastern sea cliff. The central vent lay about 2 miles out to sea to the east. The dome, after deep gulches had been cut into it by stream erosion and the margins had been cliffed by the sea, was partly submerged. The cliff on the eastern side is probably a fault scarp[37] which has retreated about 1½ miles under powerful wave attack. It probably was originally the west wall of the summit caldera.

The marine platform skirting the dome is partly submerged and partly built above sea level by Pleistocene volcanics, calcareous dunes, and alluvium. These young volcanics are called the Kiekie volcanic series and were erupted from 8 visible vents and by others now buried. Their presence was first noted by Powers.[38] They are olivine basalts[39] that issued from lava cones and vitric-lithic tuffs from Kawaihoa cone and Lehua Island.

[37] Hinds, N. E. A., op. cit. p. 93. incorrectly calls it a fault-line scarp although his text indicates that he means a battered fault scarp.

[38] Powers, S., Notes on Hawaiian petrology: Am. Jour. Sci., 4th ser., vol. 50, p. 250, 1920.

[39] A melilite-nepheline basalt was reported by Hinds but not located by the writer.

Stratigraphic rock units on the island of Niihau

Age	Rock assemblage	
	Sedimentary rocks	Volcanic rocks
Recent	Younger alluvium, playa deposits, and unconsolidated calcareous beach and dune sand	
Pleistocene	Lithified calcareous dunes, emerged marine limestone, dunes of volcanic sand, and older alluvium	Olivine basalts and vitric-lithic tuff of the Kiekie volcanic series
Great erosional unconformity		
Tertiary		Basalt and correlative dikes and plugs of the Paniau volcanic series

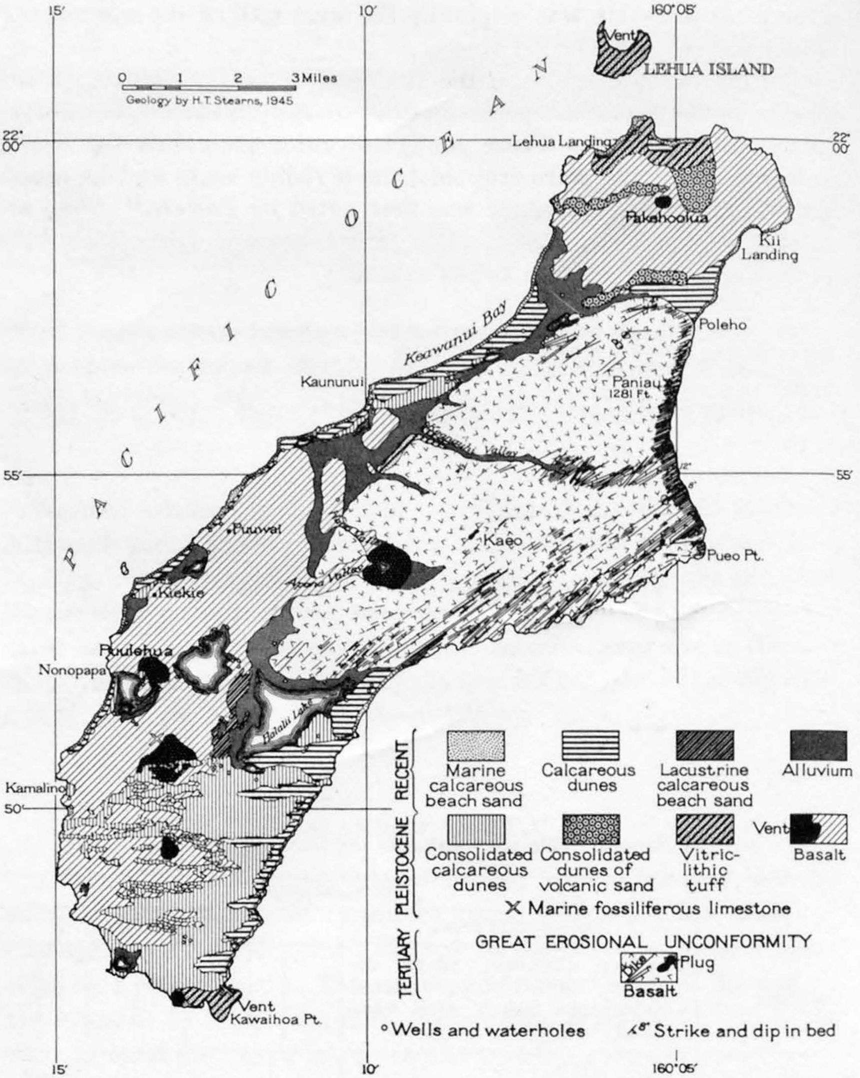

Figure 24. Geologic map of the island of Niihau. The Pleistocene basalts are named the Kiekie volcanic series and the Tertiary basalts are the Paniau volcanic series.

OFFSHORE ISLETS

Thirty-nine islets shown on plate 1 lie close to the main islands. Islets numbered 1, 2, 3, 12, 16, 23, and 33 are secondary tuff cones of late Pleistocene or Recent age. Those numbered 4, 5, 8, 20, 21, 22, 24, 25, 26, 28, 29, 30, 31, 34, 35, 36, 37, 38, and 39 are remnants of lava flows isolated from the main islands by marine erosion. Islets 11 and 15 are part of the dike complex of the Koolau Volcano; 7, 9, and 10 are lithified dunes of the Waipio terrace stage; 17, 27, and 32 are remnants of cinder cones; 13 is the remnant of a secondary nepheline basalt flow or crater fill; 19 is composed of reef limestone, Salt Lake tuff, and earthy sediments; 6 and 14 are of reef limestone of the Kapapa terrace stage; and 18 is of unconsolidated sand and is being enlarged by dredged material.

LEEWARD ISLANDS[40]

Extending northwestward from Niihau are 26 islets, reefs, and shoals known as the Leeward Islands. They mark the summits of submarine volcanoes (fig. 1). West of Gardner Island (fig. 1, no. 17), only low coral islands are found, whereas to the east many are remnants of basaltic cones. The numbers in the following classified list refer to the numbers in figure 1.

[40] Most of the data for the Leeward Islands were compiled from the following publications: Hitchcock, C. H., Hawaii and its volcanoes, pp. 1–10, Honolulu, 1909. Elscher, C., The Leeward Islands of the Hawaiian group: Reprint from Sunday Advertiser, pp. 1–68, Honolulu, 1915. Bryan, W. A., Natural history of Hawaii, pp. 94–99, Honolulu, 1915. Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands, V, The Leeward Islands: Am. Jour. Sci., 5th ser., vol. 12, pp. 336–352, 1926. Palmer, H. S. Geology of Kaula, Nihoa, Necker, and Gardner Islands, and French Frigate Shoal: B. P. Bishop Mus. Bull, 35, pp. 1–35, 1927.

VOLCANIC ISLANDS

		Height (feet)
17.	Gardner (basalt flows and dikes)	190
21.	La Perouse Pinnacle in French Frigate Atoll (basalt flows)	122
23.	Necker (basalt flows and dikes)	277
24.	Nihoa (basalt flows and dikes)	910
26.	Kaula (tuff)	550

EMERGED CORAL ATOLLS OR NEAR ATOLLS[a]

3.	Kure or Ocean (name of atoll)	—
4.	Green (sand island inside of Kure atoll)	20
6.	Midway	43
8.	Pearl and Hermes	12
9.	Lisianski	44
14.	Laysan	56

[a] The height given is measured to the top of sand dunes and does not indicate amount of emergence. The highest emerged reef known is only about 5 feet. The literature does not clearly state the evidence of emergence except for Midway and Pearl and Hermes Islands.

CORAL ATOLLS OR NEAR ATOLLS

1.	Unnamed	Breakers
2.	Bensaleux	Do
10.	Fisher	Do
11.	Minor	Do
15.	Maro (Dowsett)	Do
18.	Two Brothers	?
22.	French Frigate (excluding La Pérouse Pinnacle)	10

SHOALS (PROBABLY SUBMERGED ATOLLS)

5.	Nero	—492
7.	Gambia	— 84
12.	Neva	— 18
13.	Springbank	—108
16.	Raita	— 54
19.	St. Rogatien	— 72
20.	Brooks	— 84
25.	Unnamed	—192

Kaula is a secondary tuff cone built on a reef platform;[41] whereas the other volcanic islands are probably eroded remnants of primary volcanic domes. The rocks are composed of andesine, picrite, olivine, and nepheline basalts.[42] Andesine basalt is rare. The one specimen of nepheline basalt was collected on Necker Island from a dike which may have been the feeder to a secondary flow; but from the published description, this basalt appears to contain anemousite feldspar. If so, the lava probably belongs to the andesitic phase.

Coralline algae are the principal constituent of the living and emerged reefs. At Midway and probably at some of the nearby islands, the reefs contain an appreciable number of barnacles. The emerged reef on Midway stands 5 feet above sea level and indicates a Recent, apparently world wide, emergence of this amount.[42a]

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[41] Palmer, H. S., Geology of Lehua and Kaula Islands: B. P. Bishop Mus. Occ. Paper, vol. 12, no. 13, p. 18, 1936.

[42] Washington, H. S., and Keyes, M. G., Petrology of the Hawaiian Islands, V, the Leeward Islands: Am. Jour. Sci., 5th ser., vol. 12, pp. 336–352, 1926.

[42a] Stearns, H. T., Shore benches on North Pacific Islands: Geol. Soc. America Bull., vol. 52, pp. 773–780, 1941.

GEOLOGIC HISTORY

Much of the geologic history of the Hawaiian Islands remains to be deciphered. The long and undoubtedly complicated development of the submarine basement may never be unraveled. Practically no evidence is available to indicate when any of the Hawaiian volcanoes began. At present, only the time of extinction can be determined, and these estimations depend largely on finding lavas of younger volcanoes ponded against their neighbors so that the beds dip less where they came to rest against the adjacent dome. Erosion has exposed a few unconformities or overlaps of lavas from one cone on those from another. Using available information of the type mentioned, a tentative order of extinction has been determined. The succession from oldest to youngest is:

1. Waianae Range; 2. Koolau Range; 3. West Molokai; 4. East Molokai; 5. West Maui and Lanai; 6. Kahoolawe; 7. Haleakala. Further study may suggest changes in this order. Kauai is too far from Oahu, and Hawaii is too far from Maui for overlaps to be effective. Kohala Mountain became extinct before Mauna Kea. Hualalai, Mauna Loa, and Kilauea have erupted in historic time. The eastern part of the Niihau volcano is below sea level; hence dips cannot be used for determining the relative ages of Niihau and Kauai. The primary Kauai dome appears to be as old if not older than the Waianae Range. The age relationships of the islets and atolls stretching northwest from Kauai are unknown. These islets may be (1) large, high volcanoes planed off by fluvial and marine erosion and then submerged, (2) small low volcanoes, or (3) submarine volcanoes that approached near enough to sea level to support coral reefs. Kaula and Lehua are late cones which can be correlated with secondary cones on the other islands.[43]

Seemingly the larger, high volcanic islands were built above sea level in Tertiary time, possibly as late as the end of the Pliocene. Dana[44] states that the volcanoes became extinct from northwest to southeast. If secondary activity is disregarded, this statement is nearly true. During the soil-forming epoch, which followed extinction, drainage systems were developed and sea cliffs were cut. This erosion period was long, for deep canyons and high cliffs are found on all the islands, and lateritic soil 5 to 100 feet thick was formed.

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[43] Palmer, H. S., Geology of Lehua and Kaula Islands: B. P. Bishop Mus. Occ. Papers, vol. 12, no. 13, 1936.

[44] Dana, J. D., Geology, in U. S. Exploring Expedition, 1838–1842, vol. 10, pp. 282, 414–416, 1849.

Then followed a period of great submergence, amounting probably to more than 2,500 feet, accompanied by a new epoch of volcanism when secondary outbreaks continuing into Recent time occurred on all the major islands except Lanai. The great submergence may have been complex and at times interrupted by emergences. Next, a complex series of emergences and submergences progressed so rapidly that little reef was laid down and very little cliffing accomplished. As a present result, the islands are emerged approximately 1,200 feet or about half the amount of the previous great submergence.

Mauna Loa, Kilauea, and Hualalai have erupted in historic time. Haleakala, according to legends, erupted about 1750. Some of the other islands had secondary eruptions that antedate the latest change in sea level, a 5-foot shift downward in Recent time. Small flows overlie the Wisconsin glacial moraines on Mauna Kea.

Four stages in the geologic development of the archipelago are shown in figures 25 to 27.

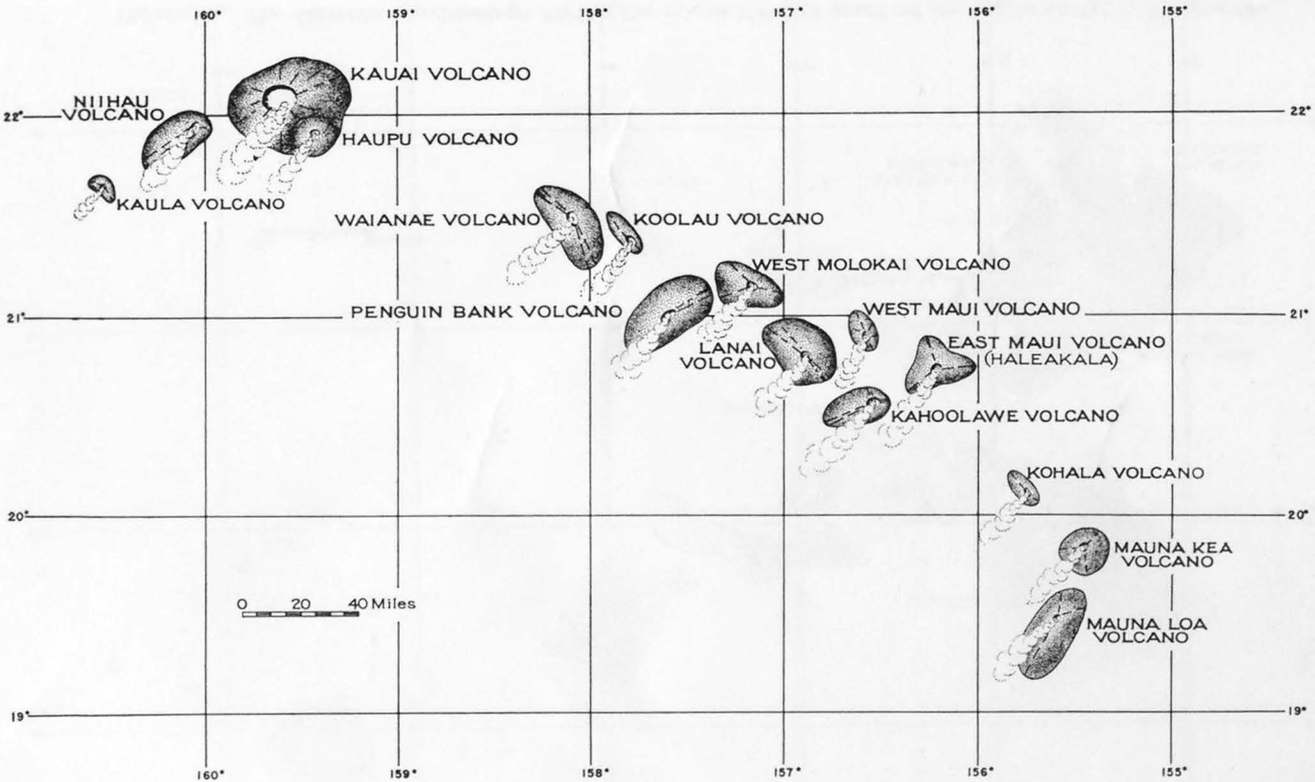

Figure 25. The Hawaiian archipelago near the end of the Pliocene.

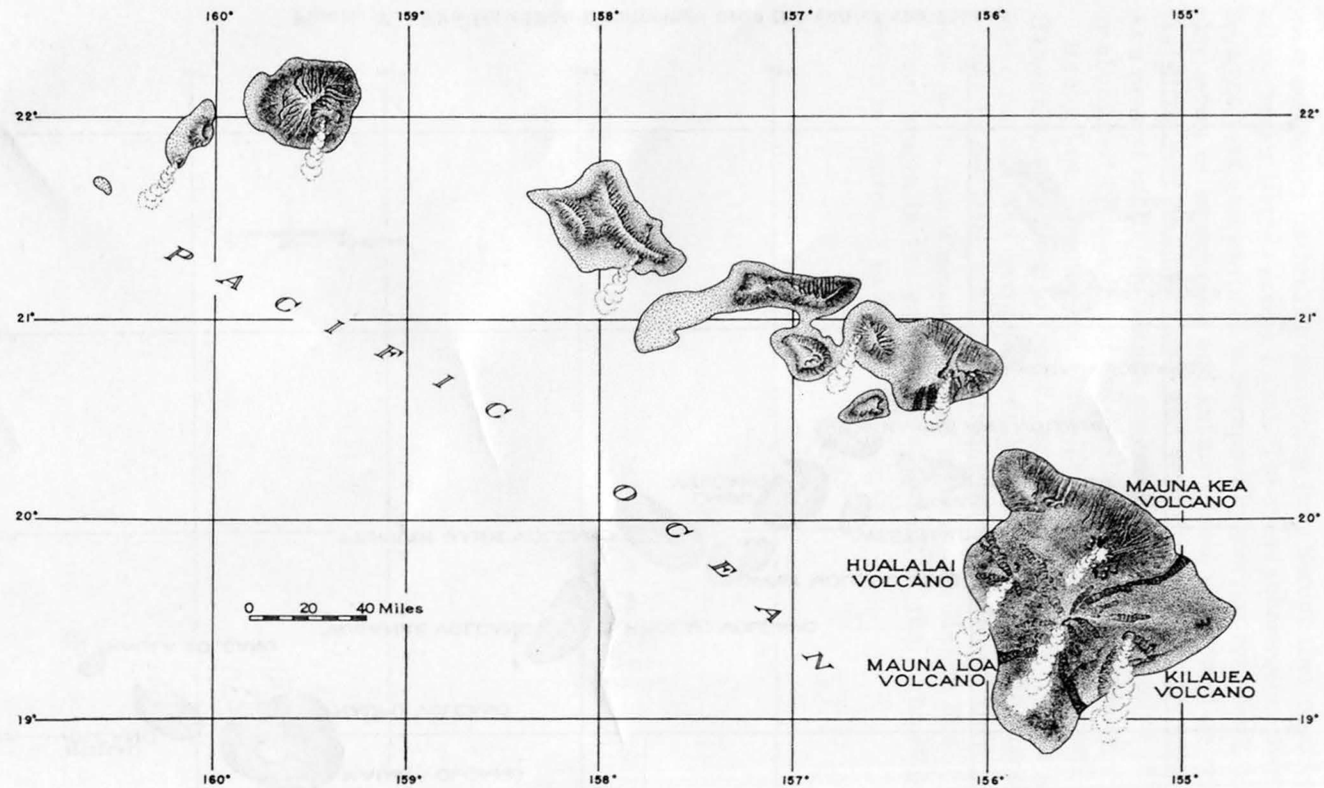

Figure 26. The Hawaiian archipelago during the minus 300-foot stand of the sea in early (?) Pleistocene.

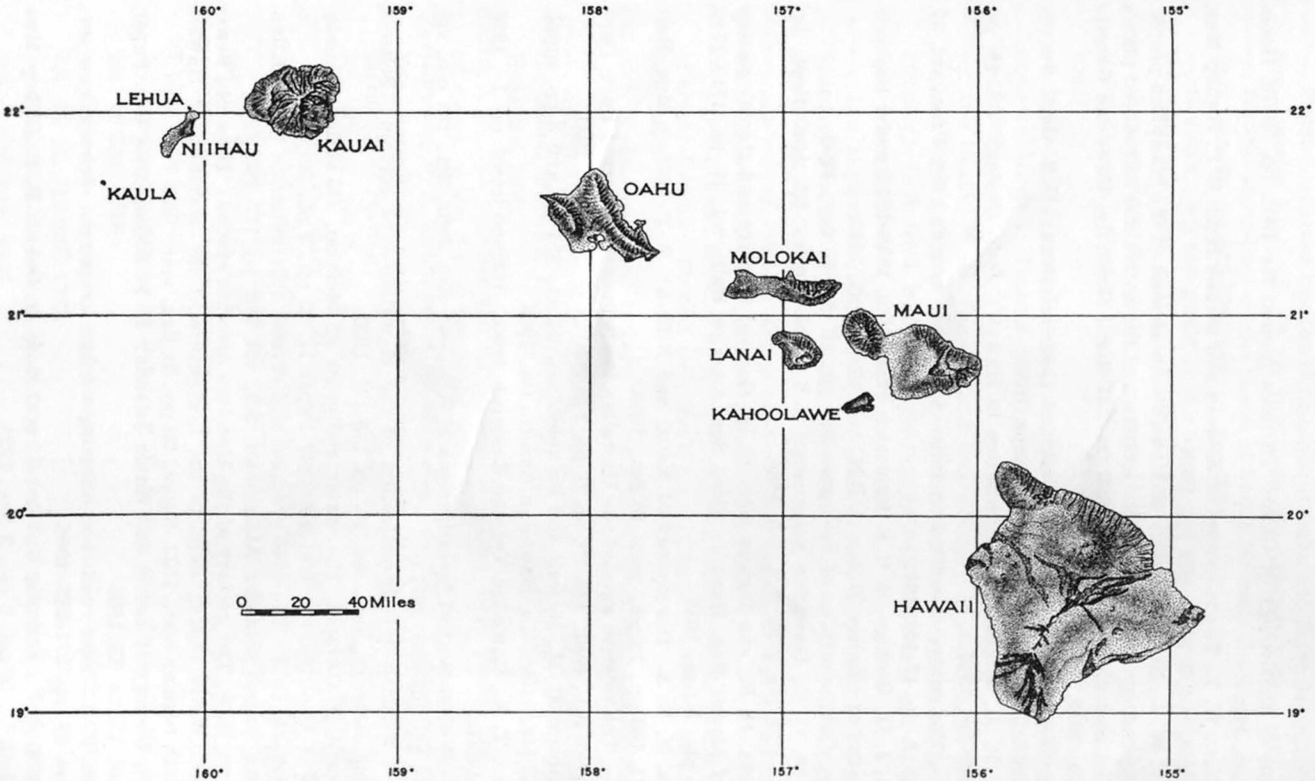

Figure 27. The Hawaiian archipelago at the present time.

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INDEX

PAGE

Abstract 1
Acknowledgments 1
Alexander, W. D., cited 34
Amphitheater-headed valleys, development 1, 7–8
formation (fig. 2) 7
view, Halawa Valley (pl. 2) 6
Ancient shore lines 14, 61, 67, 94
Ash deposits 8, 33
Atolls, age relationships........... 95
coral (fig. 1) 4, 94
emerged coral (fig. 1) 4, 93
submerged (fig. 1) 4, 94

Barnacles 94
Beach deposits 13
Bensaleux Atoll (fig. 1) 4, 94
Bering Sea 3
Betz, F., cited 16
Branner, J. C., cited 39
Breccia, Hawaii 30
vent, Oahu 78
Brooks Shoal (fig. 1) 4, 94
Bryan, W. A., cited 93

Calcareous dunes 13, 61, 67, 71, 91
Cinder cones 16, 17, 78, 93
Clark, W. O., cited 32, 33, 43, 44, 89
Cliffs (see Sea cliffs)
Climate 2–4
Cognate inclusions 38
Cones (see also under proper name)
cinder 78, 93
cinder, origin 16
cinder, profile (fig. 4) 17
fragmental, origin 16
secondary, typical profiles (fig. 4) .. 17
spatter, origin 16
spatter, profile (fig. 4) 17
trachyte 37, 59
tuff 81, 82, 93
Conglomerates 27, 56, 67, 73, 87
Coral atolls 4, 93–95
Coralline algae 94
Cross, Whitman, cited 38
"Curtain of fire" (pls. 7A, 7B) 15

Daly, R. A., cited 32
Dana, J. D., cited 95
Development, geologic, of islands (see under proper name of island)
stream 1
Deposits, ash (see also Pahala ash) .8, 33
beach 13
explosion 32
marine 13, 61, 81
Dikes 43, 49, 67, 85
view, Oahu (pl. 25) 79
widest 16
Domes, bulbous 19, 59
bulbous, profile (fig. 4) 17
bulbous, sections (fig. 6) 21
shield-shaped 16, 85
volcanic (pl. 21) 63, 64
Dunes, calcareous 13, 61, 67, 71, 91
Dunham, K. C., cited 78

PAGE

East Maui (see Haleakala)
East Molokai cliff, view (pl. 23) 70
East Molokai volcanic series 73
East Molokai Volcano 71–73
dimensions 69
extinction 95
Emerged coral atolls 4, 93
Emerged shore lines 14, 61, 67, 94
Elscher, C., cited 93
Erosion, effect of rate of 5
marine 1, 13, 63, 67, 73
stream 1, 5
wind 8
Eruption, typical 33
Eruptions (see also under name of volcano)
fissure 16
Eustatic shore lines 14

Fanglomerates (pl. 20) 59, 63
Faulting, relation to lava flows (fig. 14) 48
Faults 63, 67, 71, 91
Fisher Atoll (fig. 1) 4, 94
Fissure eruptions 16
Fragmental cones 16
French Frigate Atoll (see also La Pérouse Pinnacle) (fig. 1) 4, 94
Fringing reefs, Oahu (fig. 20) 81

Gambia Shoal (fig. 1) 4, 94
Geography 2–4
Geomorphology 5–16
Gardner Island (fig. 1) 4, 93
Graben, Kohala Mountain 39
Green Atoll (fig. 1) 4, 93
Gregory, H. E., cited 32

Halawa Valley, Molokai, view (pl. 2) . 6
Haleakala Volcano 59–61
dimensions 49
extinction 95
flow of 1750(?) 59
summit, view (pl. 13) 50
Halemaumau, 1943 eruption (pls. 9A, 9B) 24
Hamakua volcanic series 30
Hana volcanic series 61
view (pl. 13) 50
Hanalei Valley, Kauai, view ..*frontispiece*
Hanapepe Canyon, Kauai 87
Haupu (Hoary Head) Ridge 87
view (pl. 29) 88
Haupu volcanic series 87
Hawaii 25
geologic map (fig. 9) 29
historic flows (fig. 7) 25
stratigraphic units (table) 28
Hawaiian archipelago, area 2
climate 3
geographic position ....*plate* 1
geologic development (figs. 25–27) .. 97–99
profile (fig. 1) 4
rainfall 3
statistics (table) 2
submarine contours (pl. 1) 2

PAGE
submarine contours, main islands (fig. 1) 4
Hawaiian Islands, geologic history . 95, 96
origin 16
stratigraphic units (table) 23
Hawaiian volcanoes, stages of development 17–22
Hawi volcanic series 39
view (pl. 12) 43
Hess, H. H., cited 16
Hilina volcanic series 47
Hinds, N. E. A., cited 82, 90, 91
History, geologic 95
Hitchcock, C. H., cited 89, 93
Honokane Stream 38
Honokohau Canyon, view (pl. 19) 60
Honolua volcanic series 59
Honolulu volcanic series 81, 82
Honomanu volcanic series 59
Hualalai volcanic series 37
Hualalai Volcano 37–38
eruption of 1800–1801 27
height 25
last activity 38
Huehue flow 38

Iao Valley, Maui 49
view (pl. 14) 51
Introduction 1

Jaggar, T. A., cited 27, 38, 45

Kaau Crater, Oahu, view (pl. 26) 80
Kahoolawe, air mosaic map (pl. 21) 64
geologic map (fig. 16) 65
Kahoolawe Volcano, extinction 95
geologic description 63
Kahuku volcanic series 34
Kailua volcanic series 78
Kalalau Valley, Kauai, view (pl. 27) 84
Kalaupapa basalt 73
Kalaupapa Peninsula 69
Kalaupapa Volcano 73
view (pl. 23) 70
Kanapou Bay 63
Kanapou volcanic series 63
Kaneohe 78
Kapapa terrace stage 93
Kau Desert 8, 33, 43
Kau volcanic series 34
Kauai 82–90
geologic map (fig. 22) 83
stratigraphic units (table) 85
Kaukonahua Gulch, Oahu 73
Kaula Island (fig. 1) 4, 93
geologic description 94
Kaupo Valley 61
Kaupulehu flow 38
Kawaihoa Cone 91
Keanae Valley 61
Keyes, M. G., cited 93, 94
Kiekie volcanic series 91
Kilauea Volcano 43–47
eruptive cycle 46–47
explosion of 1790 44
explosions of 1924 44
height 25
historic eruptions (table) 46
hypothetical relation to earth's interior (fig. 13) 44
lava flows 45
periods of activity (fig. 8) 26
Kilohana Crater, Kauai 87
Kipahulu Valley 61

PAGE
view (pl. 13) 50
Koaie tributary, Waimea Canyon 87
Kohala Volcano 38–43
graben, description 39
height 25
historic eruptions 27
Kokokahi Peak, view (pl. 24) 76
Kolekole Pass 77
Kolekole volcanic series 77
Koloa volcanic series 87–89
"Kona winds" 3
Koolau dome, geologic development (pls. 3–6) 9–12
Koolau Range 78–82
dimensions 73
view (pl. 26) 80
Koolau volcanic series 78
Koolau Volcano, extinction 95
view (pl. 24) 76
Kula volcanic series 59
Kure Atoll (fig. 1) 4, 93

La Pérouse Pinnacle (fig. 1) 4, 93
Lahaina, Maui, view (pl. 20) 63
Lahaina volcanic series 59
Lanai 67
geologic map (fig. 17) 68
view from West Maui (pl. 22) 66
Lanai volcanic series 67
Lanai Volcano, extinction 95
Laupahoehoe Gulch 30
Laupahoehoe volcanic series 30
Lava flows, Haleakala, flow of 1750(?) 59
Huehue 38
historic, of Hawaii island (fig. 7) 25
Kaupulehu 38
Mauna Loa, flow of 1859 34
permeability 27
range in thickness 16, 33, 34
relation to faulting (fig. 14) 48
Lava lakes 47
Lava stalactites 38, 45
Laysan Atoll (fig. 1) 4, 93
Leeward Islands (fig. 1) 4
description 93–94
Lehua Island 91
Leper Settlement, Molokai 73
Limestone (fig. 20) 1, 81
Lisianski Atoll (fig. 1) 4, 93
Lualualei Valley 77

Macdonald, G. A., cited 25, 27, 36, 46
Makua Cave, Oahu (pl. 25) 79
Marine erosion 1, 13
Maro (Dowsett) Atoll (fig .1) 4, 94
Maui 49
geologic development (pls. 15–18) 55–58
geologic map (fig. 15) 52–53
stratigraphic units (table) 49
Mauna Kea Volcano 30–32
height 25
historic eruptions 27
summit, view (pl. 10) 31
view (pl. 8) 18
Mauna Loa Volcano 32–34
eruption of 1935 (pl. 11B) 35
eruption of 1940 (pl. 11A) 35
eruptions, altitude and location (fig. 10) 32
eruptions (table) 36
flow of 1859 34
height 25
hypothetical relation to earth's interior (fig. 13) 44

PAGE

periods of activity (fig. 8) 26
summit, view (pl. 8) 18
summit, view (pl. 10) 31
typical eruption 33
McAllister, J. G., cited 63
Midway Atoll (fig. 1) 4, 93
Minor Atoll (fig. 1) 4, 94
Mokuaweoweo Caldera, views (pls. 7A, 7B) 15
view (pl. 8) 18
Mokuhooniki 73
Molds, fern fronds 45
grass 45
log 87
tree 38
Molokai 69
geologic map (fig. 18) 72
stratigraphic units (table) 69
Mud flow, Maui 61

Napali Cliff, development (fig. 23) 90
Napali Coast, Kauai, view (pl. 27) 84
Nawiliwili Harbor, Kauai (pl. 29) 88
Necker Island (fig. 1) 4, 93
geology 94
Nero Shoal (fig. 1) 4, 94
Neva Shoal (fig. 1) 4, 94
Nihoa Island (fig. 1) 4, 93
Niihau 90–91
geologic map (fig. 24) 92
stratigraphic units (table) 91
Ninole volcanic series 34
Nuuanu Pali, origin 78
view (pl. 24) 76

Oahu 73–82
geologic development (pls. 3–6) 9–12
geologic map (fig. 19) 74–75
stratigraphic units (table) 77
Ocean Atoll (fig. 1) 4, 93
Olokele Canyon, Kauai 85
Offshore Islets .... *plate* 1
age relationships 95
description 93
origin 95

Pahala ash 30, 34, 43, 47
Palawai Basin 67
Palmer, H. S., cited 93, 94, 95
Paniau volcanic series 90
Pearl and Hermes Atoll (fig. 1) 4, 93
Peat bogs, Maui (pl. 19) 60
Pelekunu Valley 71
Pele's hair 33
Penguin Bank 69
Pillow lavas 17, 34, 87
Pit Craters, view (pl. 8) 18
Playa lakes, Niihau 90
Plunge-pool action 8
Pololu Valley 39
Pololu volcanic series 39
Poomau tributary, Waimea Canyon 87
Portland cement 77
Post-Koolau volcanic vents (fig. 21) 82
Powers, W. E., cited 32, 91
Pumice 33
Puna volcanic series 47
Puu Konahuanui, view (pl. 24) 76
Puu Kukui, view (pl. 19) 60
Puu Lanihuli, view (pl. 24) 76
Puu Waawaa Cone 38
lava flow from (fig. 11) 37

Raita Shoal (fig. 1) 4, 94

PAGE

Rift trends, Oahu (fig. 21) 82
Roberts, Mike, photo by .... *frontispiece*
Rocks, cliff-forming 8
coral, effect of permeability 5
effect of differences in age 5

Sea cave (Makua Cave, pl. 25) 79
Sea cliffs, development 13
formed by marine erosion 1
geologic history (fig. 3) 13
Hawaii 39
Molokai 71
Napali coast, development 89
Schofield Plateau 73
Shield-shaped domes 16, 85
Shoals (fig. 1) 4, 94
Shore lines, ancient (table) 14
emerged, Lanai 67
emerged, Maui 61
emerged, Midway 94
eustatic 14
origin 14
presence of 25-foot 27
type localities on Oahu (fig. 20) 81
Spatter cones (fig. 4) 16, 17
Sphagnum swamp 38
Springbank Shoal (fig. 1) 4, 94
St. Rogatien Shoal (fig. 1) 4, 94
Stearns, H. T., cited 5, 14, 27, 32, 33, 43, 44, 45, 61, 67, 71, 77, 78, 87, 94
Stratigraphic rock units (tables) 23, 28, 49, 69, 77, 85, 91
Stream development 1, 5
erosion 1, 5
Submarine flows 33
Submerged atolls (fig. 1) 4, 94
Sugar cane, Maui, view (pl. 20) 62

Temperature 3
The Needle, Maui 49
view (pl. 14) 51
Trachyte flow, Oahu 77
Puu Waawaa (fig. 11) 38
Trade winds 3
Two Brothers Atoll (fig. 1) 4, 94
Type section, Kahoolawe 63

Unconformity, Hawaii 34, 39
Kauai 85, 87
Kahoolawe 63
Oahu 73, 77
Unnamed coral atoll (fig. 1) 4, 94
Unnamed shoal (fig. 1) 4, 94

Valleys (Halawa, Hanalei, Kipahulu, Iao, Pelekunu, Pololu, Wailau, Waimanu, Waipio) (see under proper name)
amphitheater-headed 1, 7–8
drowned 1, 78
Volcanic island, geologic history (fig. 5) 20
Volcanic islands, description (fig. 1) 4, 93–94
origin 95
Volcanic series (East Molokai, Hamakua, Hana, Haupu, Hawi, Hilina, Honolua, Honolulu, Honomanu, Hualalai, Kahuku, Kailua, Kanapou, Kau, Kiekie, Kolekole, Koloa, Kula, Lahaina, Lanai, Laupahoehoe, Ninole, Paniau, Pololu, Puna, Wailuku, Waimea, West Molokai) (see under proper name)

PAGE

Volcanoes, "central type" 49
  eruptions (see under name of volcano)
  "fissure type" 49
  origin 1
  stages of development 12–22

Waawaa volcanics 37
Waiahulu Gulch, Kauai 85
Waialeale Plateau, Kauai 87
Waianae dome, geologic development (pls. 3–6) 9–12
Waianae Range 77
  dimensions 73
Waianae Volcano 77
  extinction 95
Waihee Canyon (pl. 19) 60
Waikapu Canyon 49
Wailau Valley 71
Wailuku volcanic series 59

PAGE

Waimanalo 78
Waimanu Valley (fig. 12)..........40–41
Waimea Canyon 85
  origin 90
  view (pl. 28) 86
Waimea volcanic series 85
Waimea Volcano 87
Waipio Stream 38
Waipio terrace stage 93
Waipio Valley (fig. 12)...........40–41
  view (pl. 12) 42
Washington, H. S., cited 93, 94
Wentworth, C. K., cited...........30, 32
West Maui 49–59
West Maui Mts., view (pl. 20) 63
West Molokai volcanic series....... 71
West Molokai Volcano 69–71
  extinction 95
Wind erosion 8
Wisconsin glacial stage 32

SUPPLEMENT

By GORDON A. MACDONALD

Senior Professor of Geology, University of Hawaii

GEOMORPHOLOGY

The following table supersedes the table appearing on page 14.

Ancient shore lines in the Hawaiian Islands[a]

Approximate altitude (feet)	Name of terrace	Approximate altitude (feet)	Name of terrace
0	Present	70	Laie
-15[b]	Koko	95	Kaena
-180[c]	Penguin Bank	55	Kahuku
-300±[d]	Mamala-Kahipa	250±	Olowalu
2	Manana	325±	(Unnamed)
5	Kapapa	375±	(Unnamed)
12[e]	Ulupau	560	Manele
25[f]	Waimanalo	625±[h]	Kaluakapo
-60±[g]	Waipio	1,200±	Mahana
45	Waialae	-1,200 to -1,800	Lualualei

[a]Modified after Stearns, H.T., Eustatic shorelines on Pacific Islands: Zeits. f. Geomorphologie, Supp. Vol. 3, p. 7, 1961.

[b]Easton, W.H., New Pleistocene shore lines in Hawaii: Geol. Soc. America, Cordilleran Sec., 61st Ann. Mtg., Program, p. 21, 1965.

[c]Placed at approximately 160 feet below sea level by Ruhe, R. V., Williams, J.M., and Hill, E.L., Shorelines and submarine shelves, Oahu, Hawaii: Jour. Geology, vol. 73, pp. 485-497, 1965.

[d]The minus-300-foot shoreline was named Mamala by Ruhe and others, op. cit., p. 486. It is the same level as previously named by Stearns the Kahipa shoreline, and Stearns (Geology of the State of Hawaii, p. 23, Palo Alto, 1966) suggests the compound name Mamala-Kahipa to avoid confusion. The minus-300-foot level probably was reached several times during glacial maxima on the continents. The last time probably coincided with the last major (Tazewell) advance of the Wisconsin glaciation, approximately 17,000 years ago. If so, it must be later than the 5- and 12-foot stands of the sea, fossil shells from which have yielded ages, by the carbon-14 method, of approximately 26,000 and 32,000 years respectively. (Ruhe, and others, op. cit., p. 494.)

[e]Named the "Ulupau Stand" by Wentworth, C.K., and Hoffmeister, J.E., Geology of Ulupau Head, Oahu: Geol. Soc. America Bull., vol. 50, p. 1571, 1939.

[f]Two shorelines, respectively 22 and 27 feet above sea level.

[g]Ruhe, and others (op. cit., p. 286), believe that -40 feet is a better value.

[h]Originally recognized by Stearns (op. cit., 1961, p. 7), but not named by him. Named by Easton (op. cit.).

GEOLOGY

ISLAND OF HAWAII

During the interval 1935-1951 there were 5 eruptions of Mauna Loa Volcano, but Kilauea remained completely inactive. In 1952 Kilauea returned to activity after a quiescence of

18 years. Since then, Kilauea has erupted 14 times, while Mauna Loa has remained entirely quiet. This 17-year quiet interval of Mauna Loa, which at the date of writing is still going on, is the longest period of quiet of Mauna Loa in recorded history.

The accompanying table gives the dates and other information on the eruptions since 1946, supplementing tables appearing on pages 36 and 46. Figure 8 on page 26 replaces the figure appearing in the first printing.

Hawaiian volcanic eruptions since 1946

(Data from Macdonald, G. A., and Hubbard, D. H., Volcanoes of the National Parks in Hawaii, Hawaii Natural History Assn., 52 pp., 1965.)

Date of commencement		Approximate duration (days)		Location of principal outflow	Altitude of main vent (ft. above sea level)	Approximate repose period since last eruption (months)	Area of lava flow (sq. miles)	Approximate volume of lava (cubic yds.)
Year	Month and day	Summit erup-tion	Flank erup-tion					
MAUNA LOA								
1949	Jan. 6	145	2	Summit	13,000	61	5.6	77,000,000
1950	June 1	1	23	SW. rift	8,000	12	35.0[a]	600,000,000[a]
KILAUEA								
1952	June 27	136	0	Halemaumau	.2,870	212.5	0.23	64,000,000
1954	May 31	3	0	Halemaumau and caldera	3,180	18.5	0.44	8,500,000
1955	Feb. 28	0	88	E. rift	150-1,310	8.9	6.1[a]	120,000,000[a]
1959	Nov. 14	36	0	Kilauea Iki	3,500	53.5	0.24	51,000,000
1960	Jan. 13	0	36	E. rift	100	0.8	4.1[a]	155,000,000[a]
1961	Feb. 24	1	0	Halemaumau	3,150	12.2	.02	30,000[b]
1961	Mar. 3	22	0	Halemaumau	3,150	0.2	.1	350,000
1961	July 10	7	0	Halemaumau	3,150	3.5	.4	17,300,000
1961	Sept. 22	0	3	E. rift	1,300-2,600	2.2	.3	3,000,000
1962	Dec. 7	0	2	E. rift	3,100-3,250	14.4	.02	430,000
1963	Aug. 21	0	2	E. rift	2,700-3,150	8.4	.06	1,100,000
1963	Oct. 5	0	1	E. rift	2,300-2,750	1.4	.6	10,000,000
1965	Mar. 5	0	10	E. rift	2,300-3,000	17.0	3.0	38,000,000
1965	Dec. 24	0	1	E. rift	3,000-3,150	9.5	.23	1,160,000

[a] Lava flow went into ocean; area given is above sea level; volume is estimated total.

[b] About 320,000 cubic yards of lava poured into Halemaumau, but most of it drained back into the vents.

ISLAND OF KAUAI

Dr. Stearns prepared the foregoing report on the geology of the island of Kauai (pages 82-90) and left the Hawaiian Islands before the geologic work on Kauai was completed. The mapping started by Stearns was finished, and the final report on Kauai was written by others.[45] The additional information that came from the later field work led to some

[45] Macdonald, G.A., Davis, D.A., and Cox, D.C., Geology and ground-water resources of the island of Kauai, Hawaii: Hawaii Div. Hydrography, Bull. 13, 212 pp., 1960.

changes in interpretation. The principal differences from Stearns' earlier report are in the interpretation of the ridge extending eastward from Knudsen Gap to Kawai Point, which we may call the Haupu Ridge; that of the origin of the Lihue Basin, north of the Haupu Ridge; and that of the origin of the lower course of the Waimea River and the country just to the east.

Stearns regarded the Haupu Ridge as the remnant of a shield volcano separate from the main Kauai shield, and centering around the mass of Haupu itself. If this were the case, the beds of lava in the west end of the ridge should dip westward. The later work showed, however, that the dips of the beds are continuously southeastward in the western part of the ridge, and parallel to those in the ridge of rocks unquestionably belonging to the main shield that lies to the west of Knudsen Gap. Structurally, the Haupu ridge is part of the main shield volcano.

The later report[45] agrees with Stearns in considering Haupu peak itself to consist of massive, nearly horizontal flows of lava that accumulated in a small caldera or very large pit crater. It differs, however, in considering the crater not to be the summit caldera of an independent volcano, but rather to be a subsidiary collapse crater on the flank of the major shield, like Makaopuhi or one of the other pit craters on the flank of Kilauea Volcano.

Stearns separated the rocks of Haupu Ridge from those of the main shield and named them the Haupu volcanic series. In the later report the rocks of the Haupu Ridge are included with those of the main volcano as part of the Waimea Canyon volcanic series. (See map, page 83.)

Stearns believed the Lihue Basin to have been formed by erosional enlargement of the heads of the two big stream-cut valleys that reached the sea respectively north and south of the Kalepa-Nonou ridge. Under that interpretation the ridge, and the nearby Aahoaka hill and Puu Pilo, represent part of the divide between the stream valleys. However, the general trend of the ridge is nearly across the supposed courses of the stream valleys, and thus approximately at right angles to the general trend of ridges that normally would be left by erosive action of consequent streams. The circular form of the basin suggests its origin by collapse in the manner of a caldera, as was suggested by Hinds[46] and this is the hypothesis adopted in the later report[47] although certainly there has been modification of the original form of the caldera by later erosion.

The hypothesis that the Lihue Basin originated by collapse has recently received support from geophysical studies, which have demonstrated the existence beneath the basin of a mass of very heavy rock similar to those found beneath other Hawaiian calderas.[48] The mass appears to be too dense to be a thick series of valley-filling lavas, and no other such dense masses have been found related to post-erosional eruptions, either on Kauai or on Oahu. It may, however, be related to the main Kauai caldera, and slightly offset from the caldera, as are the similar dense rock masses represented by gravity highs on the island of Hawaii.[49] The origin of the Lihue Basin still remains hypothetical, because the evidence that might supply the proof of origin lies buried beneath later lavas.

The lower part of Waimea Canyon cuts sharply across the southwesterly trend that is normal for consequent streams on that part of the Kauai shield volcano. Stearns (p. 90) regarded the course of the Waimea River to be the result of westward displacement of the stream by late lava flows. Physiographic studies by Palmer[50] demonstrated that an approximately north-south fault must exist along the general course of the river, as had previously been suggested by Hinds.[51] Further studies demonstrated that the Waimea fault, which is buried by later lavas, is the western edge of a graben, the other boundary of which extends about N 10° W from a point 3 miles inland from Hanapepe.[52]

Lavas from the caldera poured into the graben, partly filling it. They are shown on the geologic map (p. 83) as the Makaweli formation.

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[46]Hinds, N.E.A., The geology of Kauai and Niihau: B.P. Bishop Museum Bull. 71, p. 36, 1930.

[47]Macdonald, Davis, and Cox, op.cit., pp. 94-95.

[48]Krivoy, H.L., Baker, M., Jr., and Moe, E.E., A reconnaissance gravity survey of the island of Kauai, Hawaii: Pacific Sci., vol. 19, pp. 354-358, 1965.

[49]Kinoshita, W.T., A gravity survey of the island of Hawaii: Pacific Sci., vol. 19, pp. 339-340, 1965.

[50]Palmer, H.S., Fault at Waimea, Oahu: Pacific Sci., vol. 1, pp. 85-91, 1947.

[51]Hinds, N.E.A., op. cit., p. 79.

[52]Macdonald, Davis, and Cox, op. cit., pl. 1.

Just before and during the eruption of the lavas of the Koloa volcanic series, after the long period of erosion that followed the building of the main Kauai shield, voluminous landslides and mudflows brought down a large amount of rock debris and soil from the steep slopes of the mountainous central upland. In part, it was deposited as breccias at the foot of the steep slopes, in valley heads and along the border of the marginal lowland; but part of it was carried seaward by the streams and spread as gravels along the valleys, interbedded with the Koloa lavas. The breccias and conglomerates of this episode are indicated on the map as the Palikea formation.

AGES OF HAWAIIAN VOLCANIC ROCKS

The geologic ages assigned to the volcanic rocks in the reports published by the Hawaii Division of Hydrography were estimates based largely on the depth of weathering and erosion they had undergone. Recently, more precise dating has become possible through the use of the potassium-argon method. The following table gives the ages, based on the work of McDougall,[53] Evernden and others,[54] and Naughton and Barnes.[55]

The K-A ages are consistent with the sequence of ages determined by geologic mapping and the degree of weathering and erosion. The changes in assigned geologic ages, shown in the two right-hand columns of the table, are largely due to the fact that the present accepted duration of the Pleistocene (2 million years) is about twice that previously accepted. Perhaps the greatest surprise in the K-A dating is the very young age (less than 0.8 million years) for the Pololu volcanic series in the Kohala Mountains of Hawaii. The youngness of the rocks is supported by magnetic studies, which show them to have a normal magnetic orientation,[56] and thus to be younger than the last reversal of the earth's

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[53] McDougall, I., Potassium-argon ages from lavas of the Hawaiian Islands: Geol. Soc. America Bull., vol. 75, pp. 107-128, 1964.

[54] Evernden, J.F., Savage, D.E., Curtis, G.H., and James, G.T., Potassium-argon dates and the Cenozoic mammalian chronology of North America: Am. Jour. Sci., vol. 262, pp. 156-159, 1964.

[55] Naughton, J.J., and Barnes, I.L., Geochemical studies of Hawaiian rocks related to the study of the upper mantle: Pacific Sci., vol. 19, pp. 287-290, 1965.

[56] Doell, R.R., and Cox, A., Paleomagnetism of Hawaiian lava flows: Jour. Geophys. Research, vol. 70, pp. 3377-3405, 1965.

Ages of Hawaiian volcanic rocks

(K-A ages from McDougall, Naughton and Barnes, and Evernden, et al.)

Island	Volcano	Volcanic series or formation	K-A age (millions of years)	Geologic age	
				Previously assigned	Presently assigned
Hawaii	Mauna Loa	Ninole	0.1 -0.5	Pliocene	Pleistocene
	Kohala	Pololu	0.8	Pliocene	Pleistocene
Maui	Haleakala	Kula	0.4 -0.8	Pliocene	Pleistocene
	West Maui	Honolua	1.15-1.17	Pliocene	Pleistocene
	West Maui	Wailuku	1.27-1.30	Pliocene	Pleistocene
Molokai	East Molokai	Upper member	1.3 -1.5	Pliocene	Pleistocene
	East Molokai	Lower member	1.5	Pliocene	Pleistocene
	West Molokai	....	1.8	Pliocene	Pleistocene
Oahu	Koolau	....	2.2 -2.6	Pliocene	Pliocene
	Waianae	Upper member	2.7 -2.8	Pliocene	Pliocene
	Waianae	Middle member	2.5 -3.0	Pliocene	Pliocene
	Waianae	Lower member	2.9 -3.3	Pliocene	Pliocene
Kauai		Koloa	0.6 -1.4	Pleistocene-Recent	Pleistocene
		Makaweli	3.3 -4.0	Pliocene	Pliocene
		Napali	4.5 -5.6	Pliocene	Pliocene

magnetic field, about 0.7 million years ago. Actually, despite such large canyons as Waipio and Waimanu Valleys, the degree of erosional dissection of the Kohala Mountains is not incompatible with this young age. The interfluves between the major canyons show only a small amount of dissection.

One apparent discrepancy in age does exist, however. McDougall[57] determined the age of the Mauna Kuwale "trachyte" (rhyodacite), in the Waianae Range of Oahu, to be 8.4 million years, as compared with 3.3 to 2.5 million years for the associated lavas of the lower and middle members of the Waianae volcanic series. To explain this, he suggested that the trachyte may be the top of an older volcano buried by the Waianae lavas--a suggestion made earlier also by Stearns,[58] but not supported by the relationships found in the field.[59]

McDougall's determination of the age of the trachyte was made on grains of biotite separated from the rock,

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[57] McDougall, I., op. cit.

[58] Stearns, H.T., and Vaksvik, K.N., Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Div. Hydrography, Bull. 1, p. 181, 1935.

[59] Macdonald, G.A., and Katsura, T., Chemical composition of Hawaiian lavas: Jour. Petrology, vol. 5, p. 95, 1964.

whereas the ages of the other rocks were determined by analysis of the whole rock. It appears possible that argon may have been lost from the basalts to a greater degree than from the biotite. This is supported by Naughton and Barnes'[60] determination of 3.46 million years as the age of the trachyte on the basis of whole-rock analyses. The latter age is still, however, somewhat greater than the ages determined for the associated rocks of the middle member, to which the trachyte appears most probably to belong. This remaining discrepancy may be explained by the fact, clearly demonstrated by Funkhouser[61], that part of the argon in the biotite was derived from the original magma at the time of crystallization, instead of from the decay of potassium within the biotite.

Fossils dredged from a depth of 1650 to 1700 feet below sea level at the outer edge of a prominent terrace 6 miles southwest of Honolulu are of Miocene age.[62] The terrace is part of the Lualualei terrace of Stearns (page 14). The fossils include shallow-water corals, thus substantiating the belief that the terrace was cut by waves near sea level and has since been submerged as much as 1800 feet. Thus, island masses must have been present in the Hawaiian area during Miocene time, some 15 million years ago, and the volcanoes that make up the present major islands were built at least in part on the truncated remnants of older volcanoe The older volcanoes may well have been approximately contemporaneous with those that formed the bases beneath the limestone caps of the Leeward Islands.

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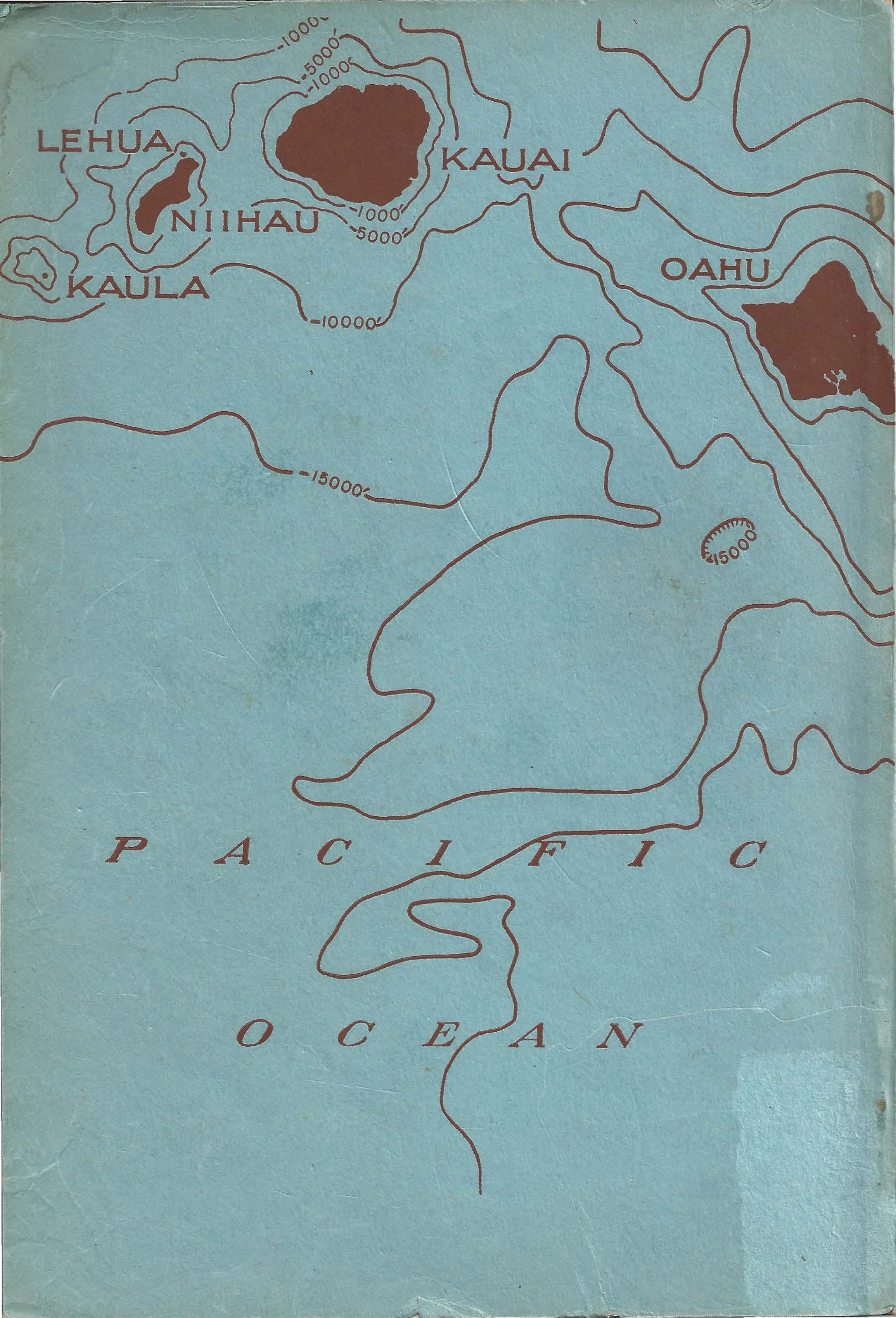
[60] Naughton and Barnes, op. cit.

[61] Funkhouser, J.G., The determination of a series of ages of a Hawaiian volcano by the potassium-argon method: unpublished thesis for the Ph.D. degree, University of Hawaii, 1966.

[62] Menard, H.W., Allison, E.C., and Durham, J.W., A drowned Miocene terrace in the Hawaiian Islands: Science, vol. 138, pp. 896-897, 1962.


LEHUA
NIIHAU
KAUAI
KAULA
OAHU
-1000'
-5000'
-10000'
-15000'
P A C I F I C
O C E A N